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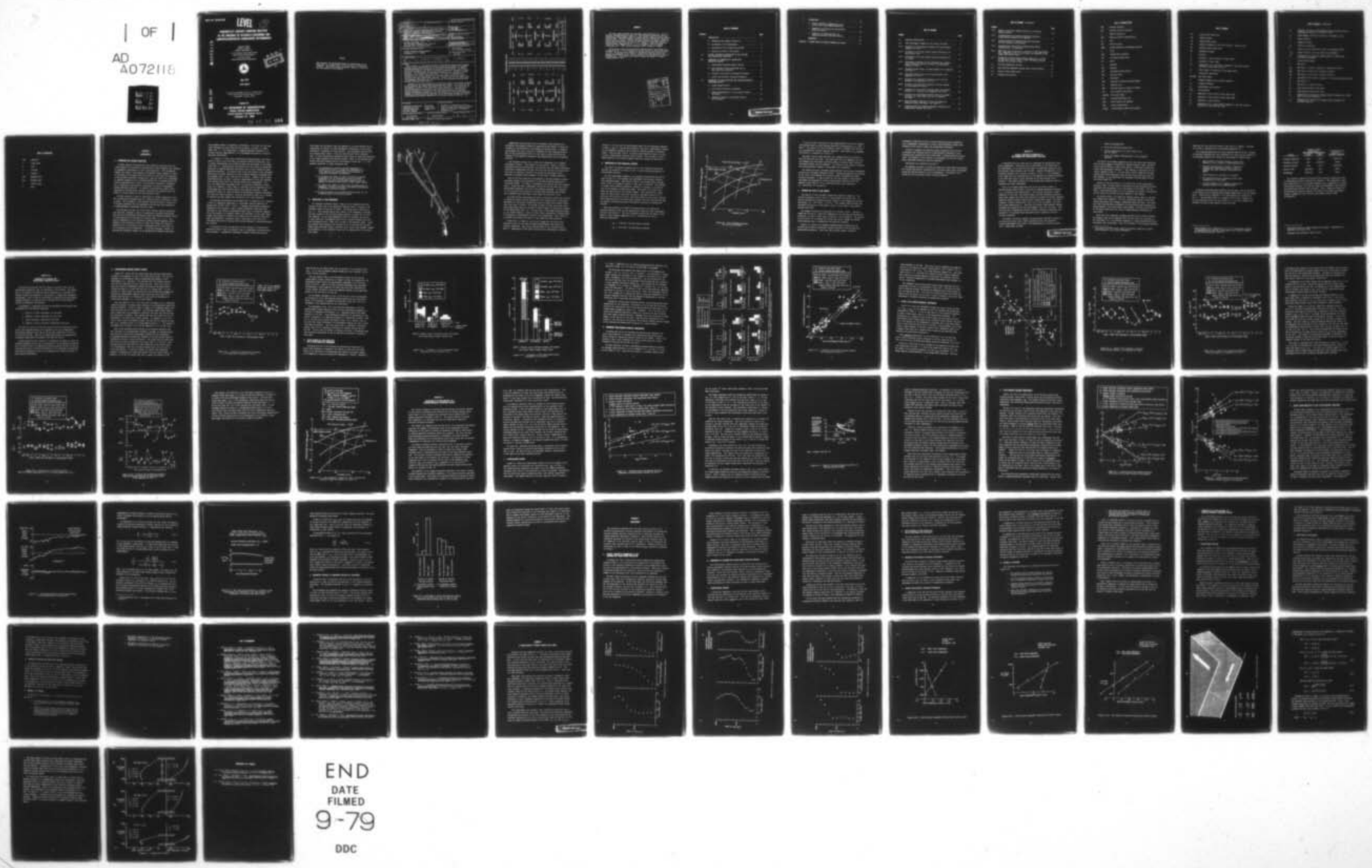

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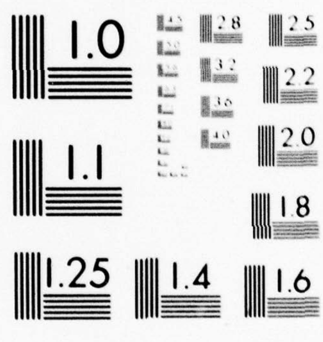

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Report No. FAA-RD-79-59

LEVEL II

POWERED-LIFT AIRCRAFT HANDLING QUALITIES IN THE PRESENCE OF NATURALLY-OCCURRING AND COMPUTER-GENERATED ATMOSPHERIC DISTURBANCES

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National Aeronautical Establishment

May 1979

Final Report

Document is available to the U.S. public through the National Technical Information Service, Springfield, Virginia 22161.

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16. Abstract

The results of a two-phased program to investigate powered-lift aircraft handling quality degradation due to both naturally-occurring and computer-generated atmospheric turbulence are presented and discussed. In Phase I an airborne simulator was used to simulate a powered-lift aircraft on final approach. The atmospheric conditions included calm air, moderate to heavy turbulence, and frontal-type wind shears. In Phase II a ground-based simulator with a moving cockpit and a colored visual display was used to represent the same powered-lift aircraft. During Phase II, the Dryden model of atmospheric turbulence was used as well as the naturally-occurring wind profiles recorded during Phase I.

Analysis of the data showed that the handling quality assessments obtained in the airborne and ground-based simulators were similar, but wind shear was responsible for more of the differences than turbulence. The comparison of the handling quality assessments and selected measures of combined pilot-vehicle performance obtained with the naturally-occurring and computer-generated turbulences demonstrate that the Dryden model can yield optimistic ratings of airplane handling qualities and an optimistic estimate of combined pilot-vehicle performance degradation in turbulent landing conditions.

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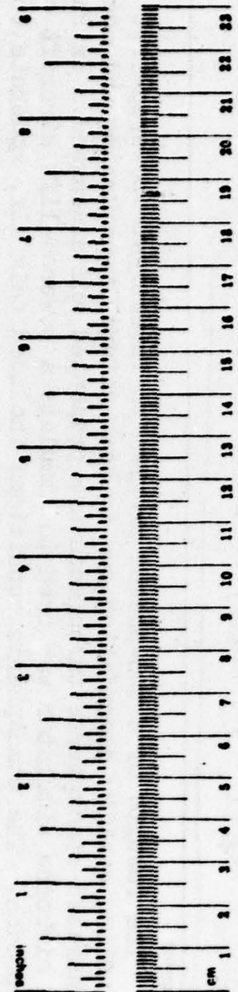
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

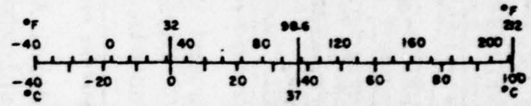
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



PREFACE

The work reported herein was performed under Modifications 1 and 8 of Contract DOT-FA77WA-3936 as part of a joint program between the National Aeronautical Establishment (NAE) of Canada and the Federal Aviation Administration (FAA). The FAA contract technical monitors were Messrs. Edward M. Boothe and Frank Hudson. The FAA assistant contract technical monitor for these contract modifications was Lt. Col. Thomas C. West, USA (Retired), the NAE project engineer was Dr. S. R. M. Sinclair, and the Systems Technology, Inc., (STI) project engineer was Mr. Warren F. Clement.

The airborne simulation experiments reported herein were planned and conducted by Dr. S. R. M. Sinclair of the NAE during the spring and winter of 1976. The ground-based simulation experiments reported herein were planned and conducted by Mr. Barry C. Scott of the FAA during the month of February 1977. This report was prepared during the months of January through March of 1979.

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LIST OF FIGURES

LIST OF FIGURES (Concluded)

LIST OF ABBREVIATIONS

ABS	Airborne simulator
ADI	Attitude Director Indicator
C	Degrees centigrade
FAA	Federal Aviation Administration
ft	Feet
FPS	Feet per second
FSAA	Flight Simulator for Advanced Aircraft
G	Great
GBS	Ground-based simulator
IFR	Instrument Flight Rules
kt	Knots
M	Moderate
MAG	Magnetic
MLS	Microwave Landing System
MSL	Mean Sea Level
N	Negligible
NAE	National Aeronautical Establishment
nm	Nautical mile
NRC	National Research Council of Canada
PIO	Pilot Induced Oscillation
rms, RMS	Root mean square
STI	Systems Technology, Inc.
STOL	Short Takeoff and Landing
VFR	Visual Flight Rules
V/STOL	Vertical/Short Takeoff and Landing

LIST OF SYMBOLS

AG	Actual glide slope error
AS	Actual airspeed
CH	Cooper-Harper rating
DW	Downward component of the wind velocity. Positive down.
EG	Estimated glide slope error
ES	Estimated airspeed
h	Altitude
h_o	Altitude of lower extremity of shear layer
H	Thickness of shear layer
HW	Along-track (i.e., east/west) component of the wind velocity. Positive for wind from the west.
L_u	Scale length of turbulence in the Dryden model
r	Correlation coefficient
rms, RMS	Root mean square
s	Complex argument of the Laplace transform
u_a	Airspeed deviation
u_g	Longitudinal gust velocity
V, V_a	True airspeed
V_H	Magnitude of wind velocity above shear layer
V_o	Magnitude of wind velocity below shear layer
V_w	Magnitude of wind velocity
XW	Cross-track (i.e., north/south) component of the wind velocity. Positive for wind from the south.

LIST OF SYMBOLS (Concluded)

Z_u	Stability derivative representing heaving acceleration due to longitudinal velocity, $(1/m)(\partial Z/\partial u)$, 1/sec
Z_w	Heave damping stability derivative, $(1/m)(\partial Z/\partial w)$, 1/sec
α	Angle of attack
γ	Flight path angle
δ_T	Throttle displacement
Δ	Prefix denoting incremental change in following variable
$\epsilon_{G/S}$	Angular deviation from the glide slope reference
ζ_h	Characteristic closed-loop damping ratio for flight path or altitude regulation
θ	Pitch attitude angle
σ	RMS value
σ_{DW}	RMS value of downward component of turbulence velocity
σ_{HW}	RMS value of along-track turbulence velocity
σ_{XW}	RMS value of cross-track turbulence velocity
σ_u	Longitudinal rms velocity component of the Dryden turbulence model
σ_x	RMS value of x
σ_x'	RMS value of x after filtering
ψ_H	Wind direction above shear layer
ψ_o	Wind direction below shear layer
ω_h	Characteristic closed-loop undamped natural frequency for flight path or altitude regulation
ω_u	Characteristic closed-loop undamped natural frequency for airspeed regulation

LIST OF SUBSCRIPTS

eff	Effective
f	Final value
g	Gust
h	Altitude
i	Inertial
max	Maximum value
min	Minimum value
o	Initial value
w	Wind

SECTION I

INTRODUCTION

A. BACKGROUND AND PROGRAM OBJECTIVES

Aircraft capable of powered-lift STOL operations generally have some common physical and operational characteristics which accentuate the influence of atmospheric disturbances on their flying qualities. STOL performance demands, for example, that approach and departure flight segments be flown at relatively low airspeeds where the effects of wind shear and turbulence on the aircraft trajectory are magnified. When the short field performance is achieved through the use of powered-induced lift or vectored thrust the handling characteristics of such a STOL aircraft operating in turbulence can be dominated by the vehicle's inherently low levels of aerodynamic damping and speed stability. In addition, the trajectory control task is compounded by unconventional response associated with operation near the bottom or on the backside of the thrust-required curve.

Problems related to flight in turbulence are further aggravated by the STOL operational environment when this includes flight in confined or built-up areas. The topography of such STOLport environs provides a complex set of boundary conditions for the atmospheric flow and may favor generation of strong mechanical turbulence and wind shears.

Over the past ten years the United States Federal Aviation Administration (FAA) has conducted a series of ground-based simulation experiments with the aim of identifying operational limits and minimum acceptable levels of flying qualities for powered-lift aircraft (Refs. 1, 2, 3, 4). The special significance of the interaction between aircraft dynamics and the dynamics of the atmosphere during low speed, STOL flight has played an important role in the design of these experiments and has been borne out by the results of pilot evaluations. It has been necessary, however, to generate the turbulence inputs for the ground-based simulator experiments

from computer models of atmospheric disturbances. The basis for the simulated turbulence has most often been the so-called "mil-spec" or Dryden model (Ref. 5). The Dryden model of computer-generated turbulence is a rational spectral approximation to the von Karman form and has a Gaussian amplitude distribution.

In contrast to these simple mathematical representations, real turbulence is found to have distinctly non-Gaussian velocity distributions and to exhibit intermittency and patchiness which are not present in the Dryden model (Ref. 6). Predictability and monotony are often cited as unrealistic qualities of computer-generated turbulence, which is also lacking in large amplitude excursions. To overcome some of the deficiencies in the turbulence models used in flight simulation several different modeling techniques have been adopted (Refs. 6 and 7 describe two of these). However, none of these statistical models includes a realistic representation of the low frequency wind variation upon which the turbulent motions are superimposed. In a real STOL operational environment these low frequency variations in wind, either as a function of time, range, or altitude, play an important role in establishing the pilot workload during final approach tracking. Simple geometrical shears are often introduced in ground-based simulator experiments but these are usually monotonic, localized disturbances which do not attempt to simulate the more complex wind variations of the real atmosphere.

The National Aeronautical Establishment (NAE) of Canada has also conducted a series of simulation experiments to investigate handling qualities of powered-lift aircraft (Refs. 8 and 9). Although these airborne simulation experiments were designed to employ computer-generated rather than real turbulence so that specific experimental tasks could be accurately repeated, it was not possible to eliminate totally the influences of real wind shears. Flights were planned to coincide with periods when the forecast winds were light and atmospheric conditions stable, nevertheless wind shears were encountered from time to time and their strong influence on tracking workload was observed.

It was upon this base of experience in the simulation of powered-lift aircraft and their flight environments that the experiments described herein were developed. A program was undertaken to measure naturally-occurring

wind shears and turbulence along the approach to an urban STOLport and to investigate the effects of these atmospheric disturbances on the flying qualities of a powered-lift STOL aircraft. The experiments entailed both an in-flight phase (Phase I) using the NAE Airborne V/STOL Simulator (Ref. 10) and a ground-based simulation phase (Phase II) which was performed on the Flight Simulator for Advanced Aircraft (FSAA) at the National Aeronautics and Space Administration's Ames Research Center (Ref. 11). The specific objectives of these experiments were:

- To investigate the handling quality degradation of powered-lift aircraft in flight while performing the final approach and landing flare in the presence of significant atmospheric disturbances.
- To determine the degree to which the airborne simulator experiment could be transferred to and its results duplicated on a modern ground-based simulator with six-degrees-of-freedom in motion and a colored visual display.
- To qualify the conditions under which the Dryden model of atmospheric turbulence provides a reasonable representation of naturally-occurring turbulence.
- To help to define a low altitude turbulence model for use in airworthiness certification testing.

B. DESCRIPTION OF THE EXPERIMENTS

The airborne evaluation flights (Phase I) were conducted within the terminal control zone of the Rockcliffe STOLport which is located at the northeast corner of the city of Ottawa. The flying task is depicted in Fig. I-1. The evaluation pilot took control of the simulator in straight and level flight at 1800 ft above runway altitude, on speed for the 65 kt STOL approach. At the model-engagement point the simulator was one dot (1 deg) below the 6 deg approach beam of the microwave landing system and was positioned one dot (3 deg) left or right of the approach course. Glide path capture and tracking to an altitude of 200 ft above ground were performed using instrument flight references and a final visual approach segment was executed to a zero sink rate flare over the landing zone of the active STOL runway.

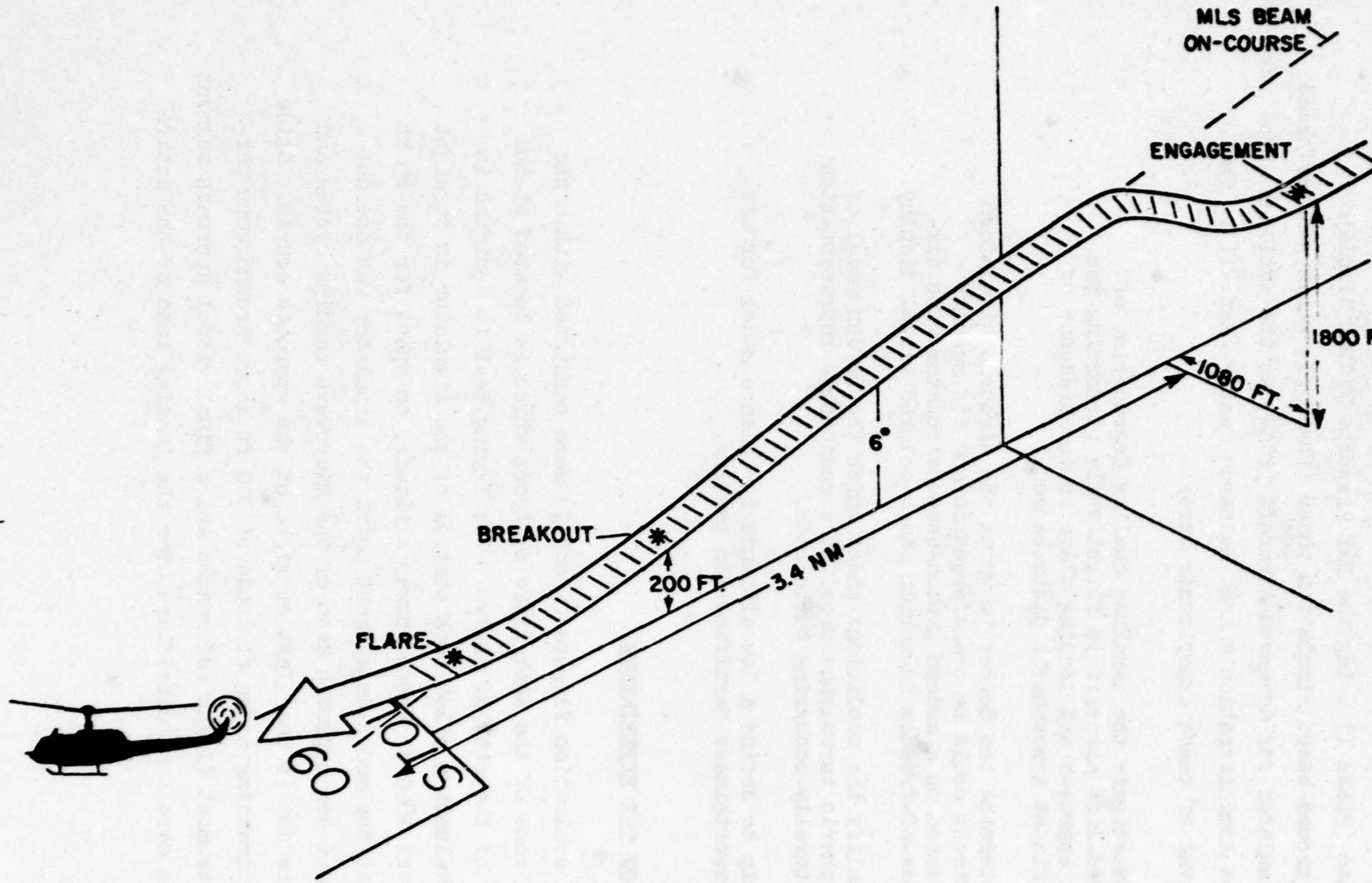

Figure I-1: Approach Tracking Task

Immediately following each run the evaluation pilot described the atmospheric disturbances during the approach and the effects of these disturbances on the difficulty of performing the tracking task. A standard questionnaire was used to provide a framework for this description and as part of this questionnaire the pilot was asked to rate the IFR and VFR segments of the approach according to the Cooper-Harper scale of handling qualities.

Four evaluation pilots flew a total of 59 approaches on 17 separate experimental flights. These numbers do not include a series of initial approaches flown by each evaluator in relatively calm and stable atmospheric conditions to familiarize the pilot with the task and with the modeled aircraft and to establish a baseline task rating and performance level. Reference 12 contains brief summaries of each pilot's flight experience.

Each of the four pilots who participated in the NAE-conducted airborne evaluation flights also participated in the FAA-conducted ground-based evaluation flights. The Phase II experiments were divided into two separate tasks. During the Task I experiments each pilot flew the same runs in the ground-based simulator as he did in the airborne simulator. In addition, all of the pilots were exposed to selected flight-recorded wind profiles that contained large wind shears and/or high rms turbulence levels.

The wind profiles used during the Task II evaluation flights were created by adding the linear velocity components of the Dryden model of atmospheric turbulence to relatively low-magnitude steady crosswind and headwind velocities (less than 15 ft/sec). No attempt was made to model wind shears other than those shears which are inherent in finite samples of turbulence generated by the Dryden model (Ref. 13). The rms level of the Dryden turbulence model, σ_u, was varied between 1.5 and 6.5 ft/sec, which corresponds to probabilities of exceedence of approximately 65% and 1.5%, respectively. These values of σ_u bounded the measured rms values of the flight-recorded turbulence.

During Task I of Phase II, at the end of each run, the pilots were required to fill out the same evaluation questionnaire used during the airborne simulation. This is the same procedure as was followed during Phase I. During Task II the pilots filled out the questionnaire extracted

from Ref. 7 (it was also the questionnaire used for the experiments reported in Refs. 14 and 15), and was used instead of the Task I questionnaire because it was designed to quantify the validity of computer-generated turbulence models. Both the Task I and II evaluation questionnaires request the pilot to give a Cooper-Harper handling quality rating. This provided a means of addressing two of the overall program objectives defined in Subsection A.

C. DESCRIPTION OF THE SIMULATION AIRCRAFT

The static and dynamic characteristics of the simulated powered-lift aircraft are described in detail in Ref. 16; the following description is intentionally succinct.

The trim performance diagram of the simulated powered-lift aircraft is shown in Fig. I-2. The aircraft trim performance was strongly backsided with decreasing speed. The positive slope of the constant pitch attitude lines in the γ-V diagram is typical of this type of aircraft. The addition of thrust, with attitude constrained, produces an increase in airspeed as well as an increase in flight path angle. With power lever fixed, trim speed was very sensitive to attitude changes. This characteristic aggravated the speed control task when tracking in turbulence because it is difficult for the pilot to close a very tight speed loop with pitch attitude. These characteristics were deliberately designed into the model because they are typical of handling qualities deficiencies prevalent in powered-lift aircraft.

There were actually two different aircraft models used during the airborne simulation (ABS) and the ground-based simulation (GBS) experiments, "Level-2" and "Level-6." The sole difference between the two models is the amount of heave damping augmentation (i.e., modification of the Z_w stability derivative):

$$Z_w = -0.88 \text{ sec}^{-1} \text{ for the Level-2 aircraft}$$

$$Z_w = -0.57 \text{ sec}^{-1} \text{ for the Level-6 aircraft}$$

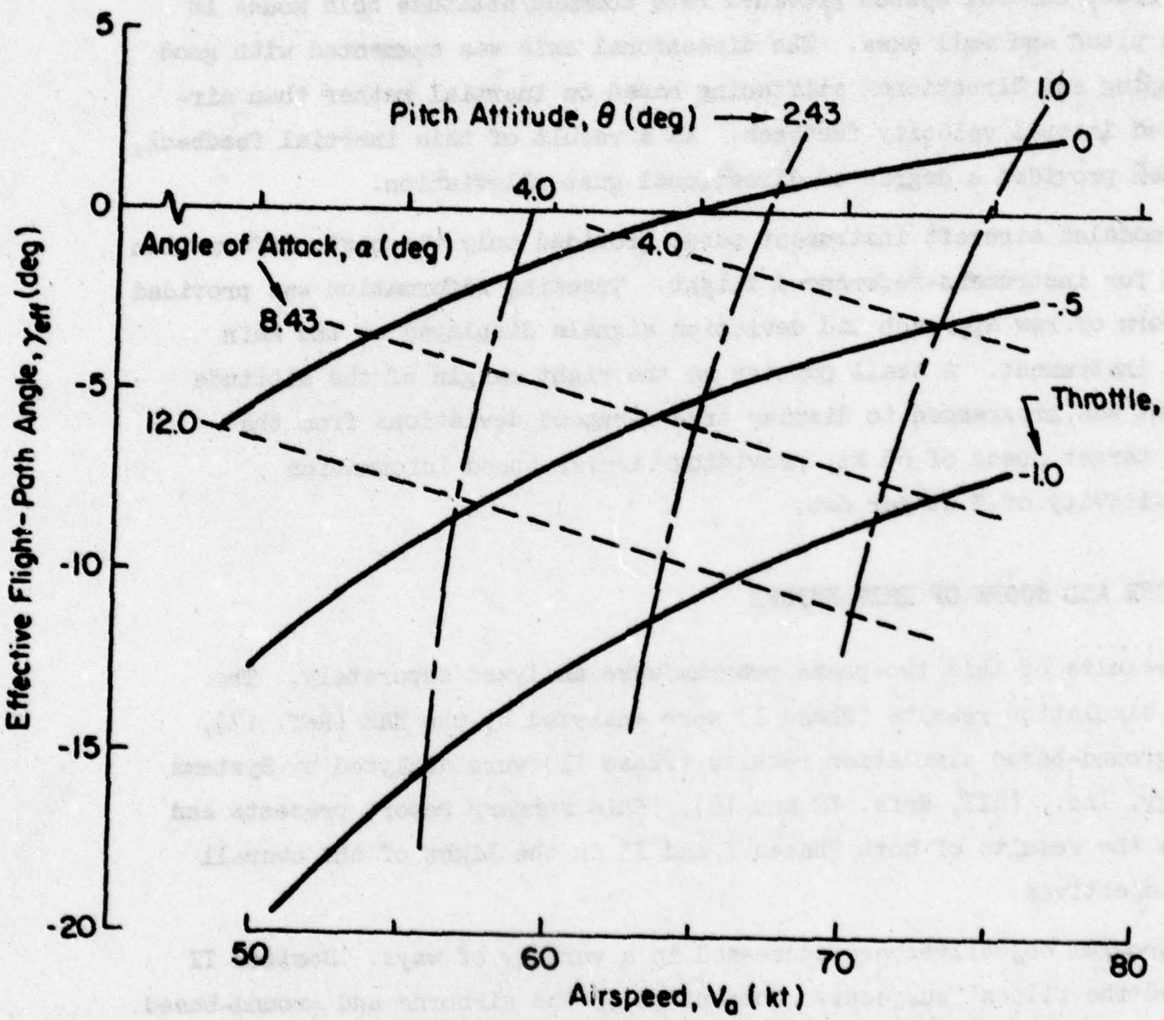

Figure I-2. Trim Performance Diagram For the Level-6 Aircraft

Z_w for the Level-6 aircraft was more representative of that for powered-lift aircraft used in other handling qualities investigations (e.g., Refs. 2 and 4). Two values of Z_w were included in order to document the effects of Z_w on powered-lift aircraft handling qualities. More about the Z_w augmentation efforts is presented in Section IV.

The model control system provided rate command/attitude hold modes in both the pitch and roll axes. The directional axis was augmented with good rate damping and directional stiffening based on inertial rather than air-referenced lateral velocity feedback. As a result of this inertial feedback, the system provided a degree of directional gust alleviation.

The modeled aircraft instrument panel provided only the basic information required for instrument-referenced flight. Tracking information was provided in the form of raw approach aid deviation signals displayed at the main attitude instrument. A small pointer at the right margin of the attitude instrument was programmed to display true airspeed deviations from the approach target speed of 65 kt, providing vernier speed information at a sensitivity of 5 kt per dot.

D. PURPOSE AND SCOPE OF THIS REPORT

The results of this two-phase program were analyzed separately. The airborne simulation results (Phase I) were analyzed by the NAE (Ref. 17), and the ground-based simulation results (Phase II) were analyzed by Systems Technology, Inc., (STI, Refs. 12 and 18). This summary report presents and discusses the results of both Phases I and II in the light of the overall program objectives.

The program objectives are addressed in a variety of ways. Section II summarized the pilots' subjective comparison of the airborne and ground-based simulators, as well as their major criticisms of each simulator. The purpose of this section is to document how closely the pilots thought the ground-based simulator came to representing the airborne simulator.

Section III presents and compares handling quality ratings and some selected pilot-vehicle performance measures obtained in the airborne and ground-based simulators. These data were obtained under a variety of

atmospheric conditions and thus document handling qualities degradation due to atmospheric disturbances as well as the differences between data obtained in the airborne versus the ground-based simulators.

Section IV compares the handling quality ratings and pilot-vehicle performance data obtained with the flight-recorded turbulence to the analogous data obtained with the Dryden model of computer-generated turbulence. The purpose of this section is to determine how well the Dryden model represents naturally-occurring turbulence.

Conclusions are contained in Section V.

The appendix describes a relatively simple wind shear model which matches the overall wind profile characteristics of frontal shear layers encountered during the airborne portion of this investigation. The model is well suited for use in realtime piloted aircraft simulators.

SECTION II

PILOTS' SUBJECTIVE IMPRESSIONS OF THE AIRBORNE AND GROUND-BASED SIMULATORS

A validation pilot was used prior to conducting the ground-based simulation experiments. This pilot did not participate in the formal NAE or FAA experiments, but he does have many hours of experience flying both the NAE Airborne V/STOL Simulator and the FSAA. Complete documentation of this validation exercise can be found in Section V of Ref. 16. The validation pilot judged that the characteristics of the powered-lift aircraft simulated on the FSAA were close to those simulated on the NAE Airborne V/STOL Simulator. This added credibility to the ground-based simulation prior to beginning the formal experiments.

Prior to the formal experiments each pilot was given a number of familiarization flights using a low level of computer-generated turbulence (σ_u = 1.5 ft/sec in the Dryden model). This allowed the pilots to adapt themselves to the task, the aircraft model, and FSAA operating procedures. After these flights the pilots were required to respond to specific questions regarding control strategy (speed control, flight path control, and control coupling), control sensitivities (pitch, roll, yaw, and power), and force feel system characteristics. They were also asked to make general comments regarding the simulation and the task segments (IFR, VFR, and flare). The resulting pilot commentaries provided valuable information regarding pilot acceptance of the ground-based simulation and its comparison with the airborne simulation.

In general, the pilots regarded the ground-based simulator fidelity to be quite good in most areas ("FSAA simulation better than expected," "aircraft performance and control very representative of airborne simulator"). These areas included:

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1. Cockpit instrumentation

2. Force feel system characteristics

3. Control sensitivity in all axes (pitch, roll, yaw, and power)

4. Static and dynamic characteristics of the simulated aircraft.

The pilots' most common complaint was with the visual cues during the VFR and flare segments ("essential to monitor attitude, speed, and glide slope even when visual to avoid large errors," "difficult to assess the flight path performance visually"). This finding is consistent with the results reported in Ref. 2. In that study a direct comparison was made between IFR and VFR approaches using the same visual display as used in this program. It was found that PIO tendencies existing under VFR were not present under IFR.

Because of the deficiencies in the visual cues in the ground-based simulator (GBS), the main effort in analyzing the data resulting from both simulators was concentrated in the IFR portion of the flight. The old adage "a good approach makes for a good landing" can be used to extrapolate the IFR results to the VFR and flare segments of the landing.

The adverse effects of hitting the vertical motion limits in the FSAA was another pilot complaint. This was occasionally caused by the pilots making large power lever changes, especially during the flare. The pilots said they could partially compensate for this motion system limitation by making smoother, less abrupt power lever changes. The noise and vibration of the motion system was also cited as being annoying (distracting) to some pilots*.

There were also complaints regarding the NAE Airborne V/STOL Simulator. For example, some pilots commented that the rotor noise and vibration in the helicopter (i.e., the airborne simulator is a highly modified Bell 205A helicopter) were distracting. Also, the "breakout" in the airborne simulator

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* The sound of the FSAA motion system is partially masked by an engine noise simulator, but is still discernable.

(ABS) was not very realistic because a hood had to be removed. (Breakout in the GBS is simulated with electronically generated fog.)

The following generalizations can be inferred from the pilots' response to questions regarding what they considered to be good and poor features of the simulated powered-lift aircraft for performing the required task:

1. Speed control is difficult because of poor speed stability, but is critical to performing the task.
2. Aircraft characteristics required a "backsided" technique for longitudinal control (control of airspeed with pitch attitude, flight path with power).
3. Power response was considered too sluggish*.
4. The lateral-directional handling qualities were considered to be quite good.
5. A strong headwind on the approach reduced pilot workload because of the lower sink rate.

Following the ground-based simulation the NAE sent a list of questions to the subject pilots regarding their general impressions of the two simulations. Detailed pilot responses to the questionnaire are contained in Ref. 12. The following table is a synopsis of the pilots' comparison of the two simulators versus the "real world" (i.e., an actual powered-lift aircraft) as well as one simulator versus the other:

* Engine dynamics were simulated with a 0.75 sec first-order lag which is representative of the lag in high bypass ratio turbo-fan engines used in some powered-lift aircraft.

Feature	Simulator Versus Real World* NAE Airborne V/STOL	Simulator Versus Real World* Ground-Based FSAA	Ground-Based with Respect to Airborne Simulator†
Aircraft Simulation	Good	Good	Equivalent
Instrument Display	Fair	Excellent	Better
Aircraft Controls	Good	Good	Equivalent
Field of View	Excellent	Poor	Worse
Environment	Excellent	Fair	Worse

The subjective impressions discussed above provide a qualitative basis for addressing Objective 2 described in Section I. The conclusion is that most characteristics of an airborne simulator can be reproduced on a modern ground-based simulator, but that the visual cues presented in this particular ground-based simulator were deficient. Thus a comparison between the ground-based and airborne simulator IFR results can be made confidently, whereas a comparison of the VFR and flare results should be made circumspectly.

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* "Real World" means an actual powered-lift aircraft. Categories are Excellent, Good, Fair, Poor.

† Categories are Equivalent, Better, Worse.

SECTION III

COMPARISON OF AIRBORNE AND GROUND-BASED SIMULATION RESULTS

Selected data resulting from the airborne simulation (ABS) and the ground-based simulation (GBS) are presented in this section. The purpose here is to document the handling quality degradation of a powered-lift aircraft during final approach in the presence of significant atmospheric disturbances. This is done by presenting and comparing the Cooper-Harper ratings obtained in the ABS and GBS by the same pilot flying through a variety of atmospheric disturbances.

For purposes of presenting the data the atmospheric disturbances were classified into four general categories:

1. Calm air to light turbulence, no wind shear
2. Moderate to heavy turbulence, no wind shear
3. Light turbulence, significant wind shear
4. Moderate to heavy turbulence, significant wind shear

The data for only one of the four subject pilots are presented herein. Pilot D was selected because he was exposed to all of the atmospheric disturbances described above and he had the most complete set of data on both the ABS and GBS. Data for the other three pilots were examined and in general corroborated the trends in the data for Pilot D.

Another purpose of this section is to determine the degree to which the airborne simulation results can be duplicated in the ground-based simulator. This is done not only by comparing the handling quality ratings but also by comparing the pilot's subjective impression of the atmospheric disturbances and vehicle performance as well as by comparing some selected measures of pilot-vehicle performance.

A. COOPER-HARPER HANDLING QUALITY RATINGS

Figure III-1 shows both the ground-based and airborne Cooper-Harper ratings on the approach for one of the four subject pilots. The data are presented in chronological order to demonstrate any trends in skill development (i.e., learning). The data show that the ratings obtained from the two simulators are only rarely the same. There are, however, many runs where the differences between the airborne and ground-based ratings are equal to or less than one half of a rating point. We call attention to this because the variations in the ratings within <u>either</u> the airborne or ground-based simulator results are very often equal to or greater than one half of a rating point, even when the disturbance is effectively unchanged (i.e., on the same flight).

Also note from Fig. III-1 that there does not appear to be a consistent trend for superior or inferior pilot ratings in the ground-based versus the airborne simulator. There do, however, appear to be learning trends in the data resulting from both simulators. The learning trends appear within a given flight where the atmospheric conditions, and hence the wind profiles, are effectively unchanged. This implies that the pilot learns to "fly the disturbance," and hence gives better ratings. For example, on Run 175-2 Pilot D had to abort the airborne flight, but was able to complete the next Run 175-3, although he gave it a Cooper-Harper rating of 7. The ratings on subsequent runs of Flight 175 in the ABS improved to a 5.5 on Run 175-9.

Some of the learning trends observed in the airborne simulator were also observed in the ground-based simulator, although, as discussed above, there was not a one-to-one correspondence between the two simulations. An important difference between the scenarios of the ABS and GBS could be responsible for some of these differences. The pilots were not aware that each run in the GBS was presented in the same order as in the ABS. Thus, although the pilots were given the wind conditions on the surface prior to the beginning of each run, the pilots treated each run in the GBS as a new wind profile. In the ABS, however, the pilots were repeatedly exposed to essentially the same wind profile within any given flight. In addition, in the ABS the pilots were able to gauge the severity of the

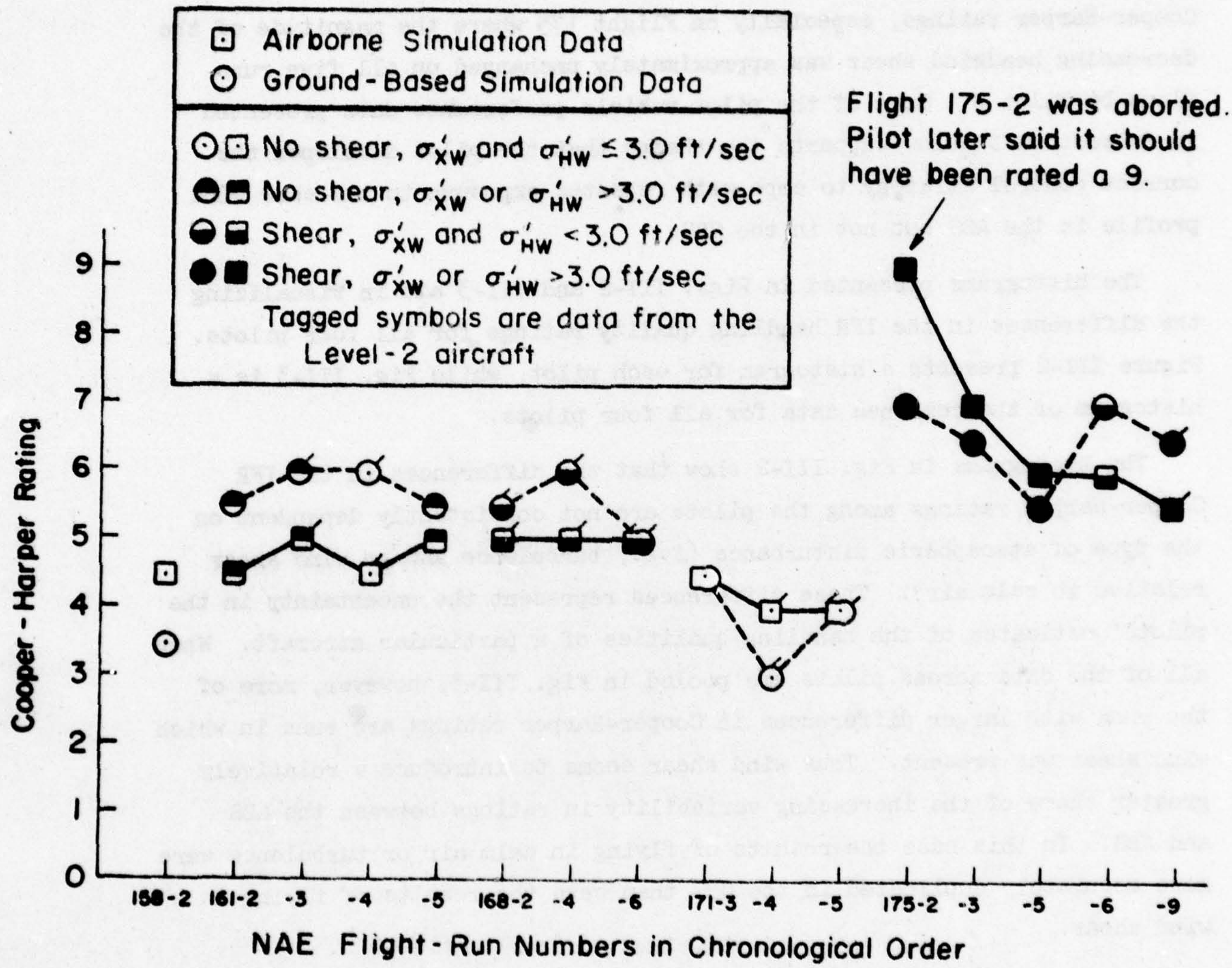


Figure III-1. Airborne and Ground-Based Simulator IFR Cooper-Harper Ratings for Pilot D

wind profile as the safety pilot flew the aircraft to its initial condition. In the GBS the digital computer simply puts the "aircraft" at its correct initial position.

This may explain some of the differences between the ABS and GBS Cooper-Harper ratings, especially on Flight 175 where the magnitude of the decreasing headwind shear was approximately unchanged on all five runs flown by Pilot D. Some of the pilot-vehicle performance data presented in Subsection D below supports the theory that the pilot developed the correct control strategy to cope with repeated exposure to the same wind profile in the ABS but not in the GBS.

The histograms presented in Figs. III-2 and III-3 aid in visualizing the differences in the IFR handling quality ratings for all four pilots. Figure III-2 presents a histogram for each pilot, while Fig. III-3 is a histogram of the combined data for all four pilots.

The histograms in Fig. III-2 show that the differences in the IFR Cooper-Harper ratings among the pilots are not consistently dependent on the type of atmospheric disturbance (i.e., turbulence and/or wind shear relative to calm air). These differences represent the uncertainty in the pilots' estimates of the handling qualities of a particular aircraft. When all of the data across pilots are pooled in Fig. III-3, however, more of the runs with larger differences in Cooper-Harper ratings are runs in which wind shear was present. Thus wind shear seems to introduce a relatively greater share of the increasing variability in ratings between the GBS and ABS. In this case the results of flying in calm air or turbulence were more accurately duplicated in the GBS than were the results of flying in wind shear.

B. PILOT RATINGS OF TASK DIFFICULTY DUE TO WIND SHEAR AND TURBULENCE

Following each run in the airborne and ground-based simulators the pilots were requested to categorize the effects of wind shear and turbulence on the difficulty of accomplishing the capture-to-breakout segment of the approach by using the adjectives "Negligible," "Slight," "Moderate,"

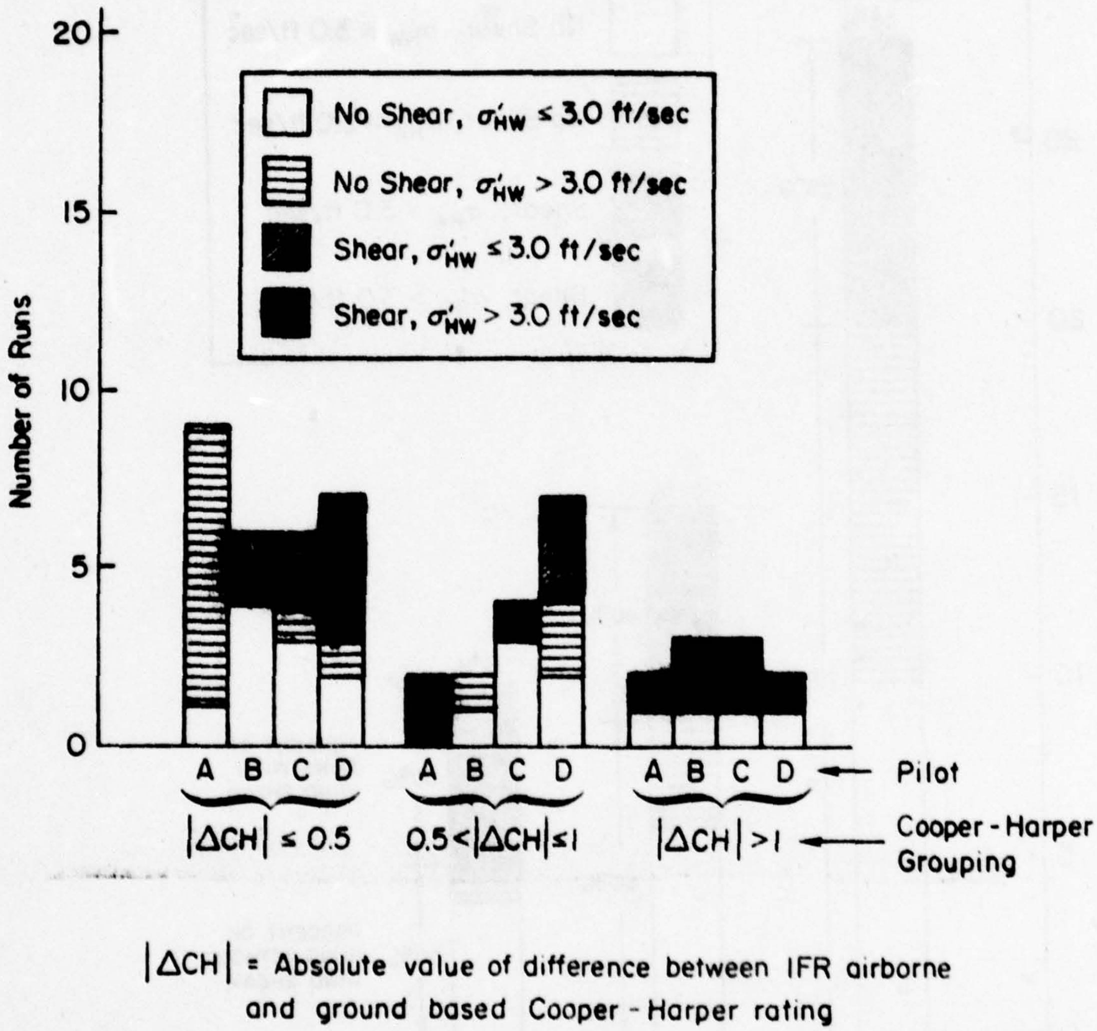
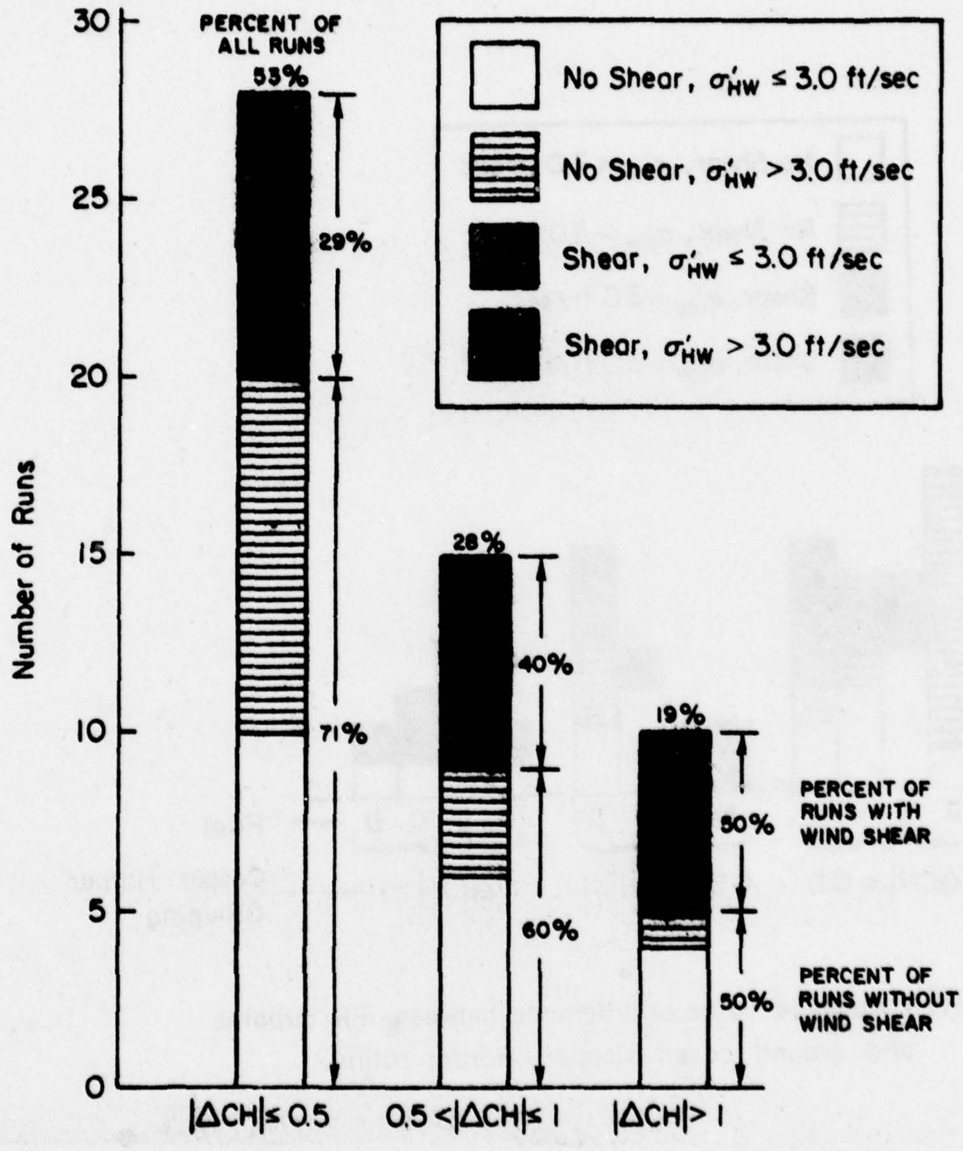


Figure III-2. Histograms of IFR Cooper-Harper Rating Differences for Each Subject Pilot



$|\Delta CH|$ = Absolute value of difference between IFR airborne and ground based Cooper - Harper rating

Figure III-3. Histograms of IFR Cooper-Harper Rating Differences for All Pilots

or "Great." Data from both the airborne and ground-based simulators are presented in Fig. III-4 for Pilot D in the form of histograms.

The estimates were grouped into three levels of IFR Cooper-Harper ratings (4 to 4.5, 5 to 5.5, and 6 or greater). For each group of Cooper-Harper ratings the histograms of the estimate of difficulty due to wind shear, turbulence, and "Sum" are presented. The Sum distributions are the sum of the wind shear and turbulence distributions and thus represent a total external disturbance rating (i.e., the ordinate is the frequency of assignment of all ratings of "Negligible," "Slight," etc., due to wind shear and turbulence). The medians of the Sum distributions are indicated by arrows at the base of each distribution. Thus, the histograms shown in Fig. III-4 enable one to compare the pilot's subjective impression of the aircraft handling qualities with his subjective impressions of the task difficulty due to wind shear and turbulence.

Although the distributions obtained from the airborne and ground-based simulations are not identical, the medians of the ABS and GBS Sum distributions both consistently shift toward greater perceived difficulty as the Cooper-Harper ratings get poorer (i.e., increase). Also, runs that contained wind shear and turbulence tended to be perceived as more difficult and rated poorer in both simulators, although there were exceptions to these trends in both the ABS and GBS data. Thus the pilots perceived the influence of the atmospheric disturbances and assigned handling quality ratings in the airborne and ground-based simulators in a similar manner.

C. ESTIMATED PILOT-VEHICLE TRACKING PERFORMANCE

Following each run in the airborne and ground-based simulators the pilots were requested to estimate their maximum speed and glide slope errors during the capture-to-breakout portion of the flight. Figure III-5 presents a plot of the estimated (ES) versus actual speed (AS) errors obtained in both the ABS and GBS for Pilot D.

The data show that the pilot consistently underestimated his maximum and minimum speed deviations in both simulators (e.g., he said +5 kt when he was really +10 kt). Also note that there is a tendency toward better

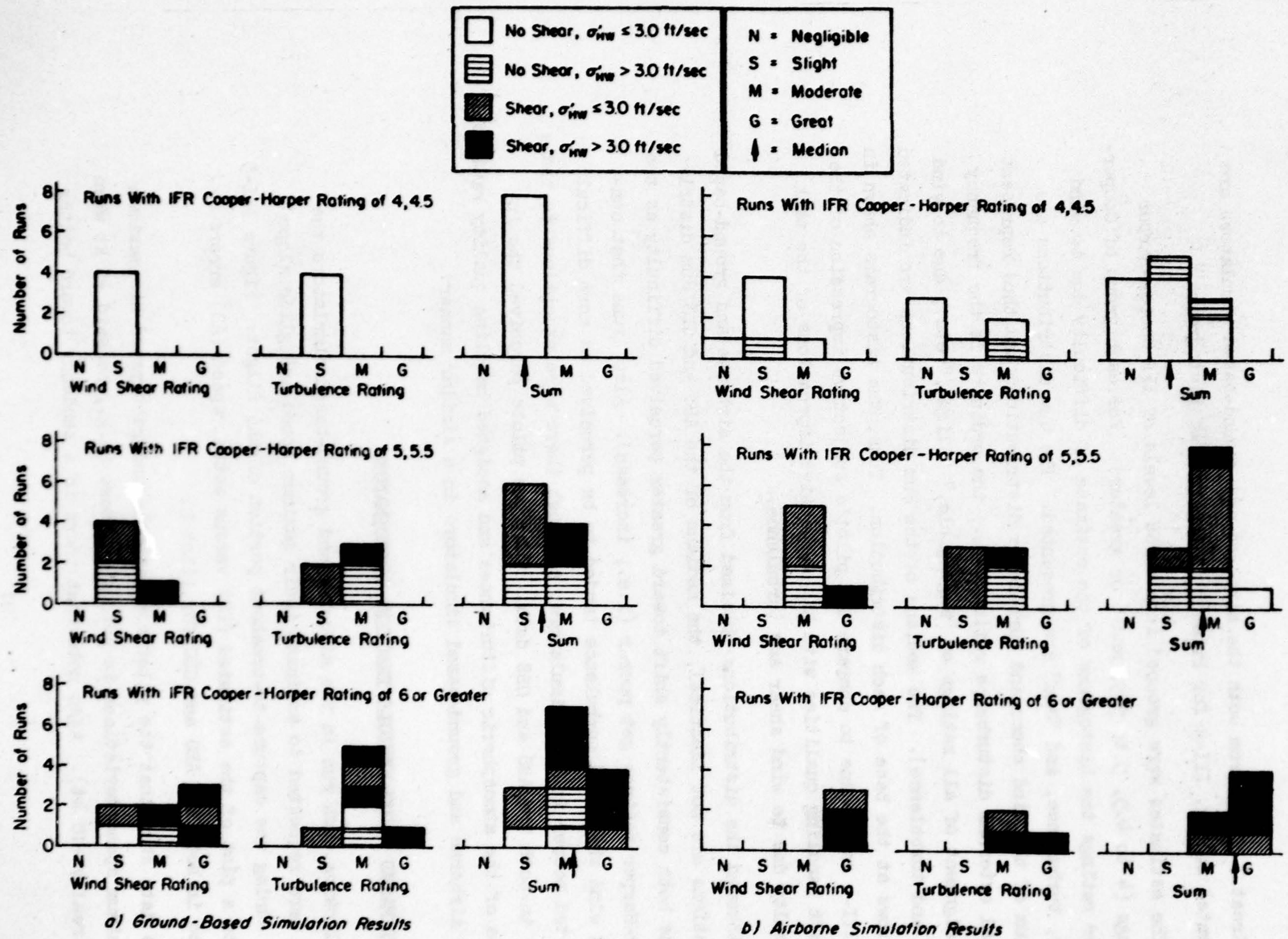


Figure III-4. Histograms of Ratings of Task Difficulty Due to Shear and/or Turbulence For Three Ranges of Cooper-Harper Ratings by Pilot D

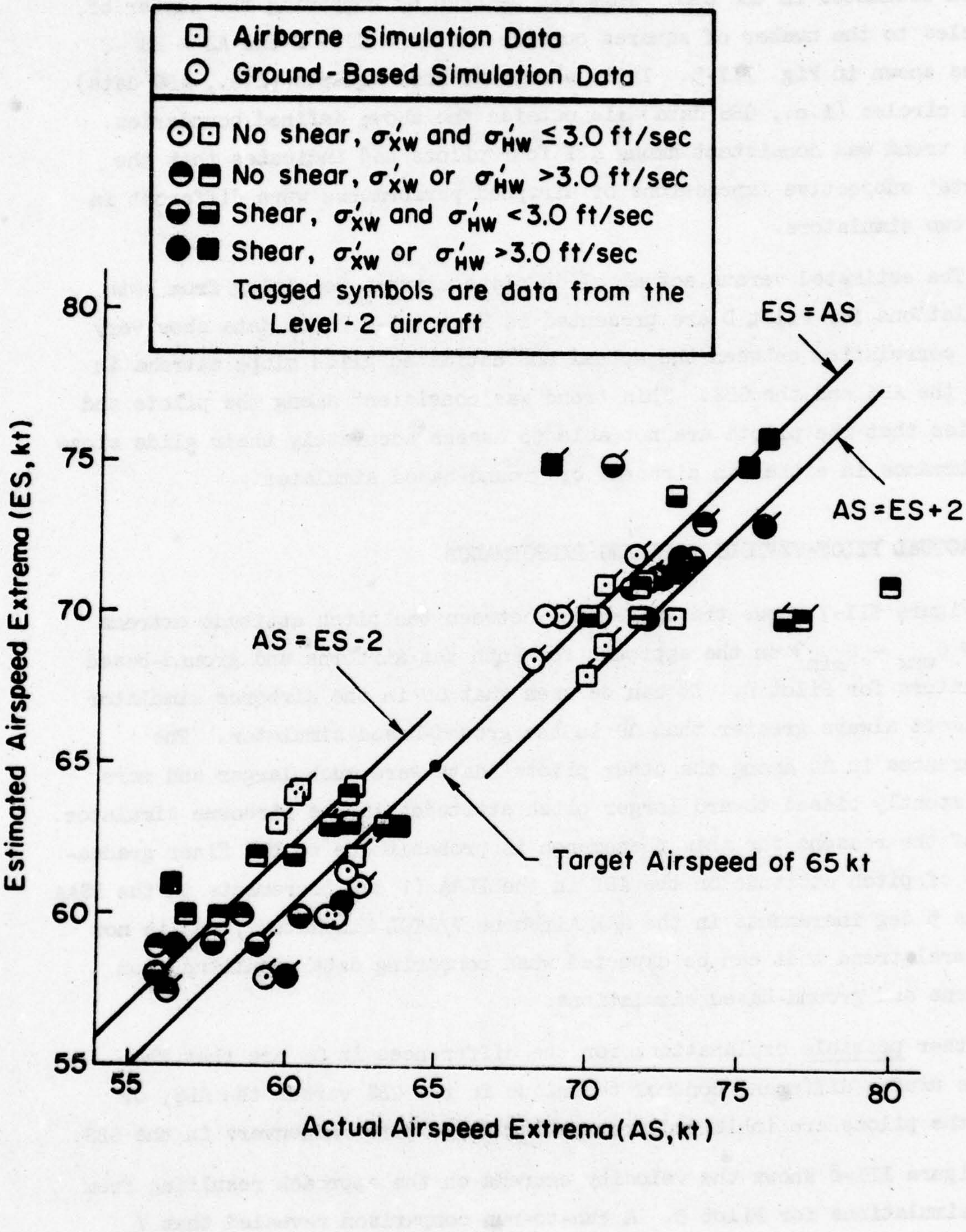


Figure III-5. Estimated Versus Actual Airspeed Extrema on the Approach for Pilot D

speed estimates in the GBS. This can be seen by comparing the number of circles to the number of squares outside the AS = ES + 2 and AS = ES -2 lines shown in Fig. III-5. It is seen that more squares (i.e., ABS data) than circles (i.e., GBS data) lie outside the above defined boundaries. This trend was consistent among all four pilots and indicates that the pilots' subjective impressions of airspeed performance were different in the two simulators.

The estimated versus actual glide slope extrema resulting from both simulations for Pilot D are presented in Fig. III-6. The data show very poor correlation between the actual and estimated glide slope extrema in both the ABS and the GBS. This trend was consistent among the pilots and implies that the pilots are not able to assess accurately their glide slope performance in either an airborne or ground-based simulator.

D. ACTUAL PILOT-VEHICLE TRACKING PERFORMANCE

Figure III-7 shows the difference between the pitch attitude extrema ($\Delta\theta \equiv \theta_{max} - \theta_{min}$) on the approach for both the airborne and ground-based simulators for Pilot D. It can be seen that $\Delta\theta$ in the airborne simulator is almost always greater than $\Delta\theta$ in the ground-based simulator. The differences in $\Delta\theta$ among the other pilots' data were much larger and more consistently biased toward larger pitch attitudes in the airborne simulator. One of the reasons for this phenomenon is probably due to the finer graduations of pitch attitude on the ADI in the FSAA (1 deg increments in the FSAA versus 5 deg increments in the NAE Airborne V/STOL Simulator), and is not a general trend that can be expected when comparing data resulting from airborne and ground-based simulations.

Other possible explanations for the differences in $\Delta\theta$ are that the pilots used a different control technique in the GBS versus the ABS, or that the pilots are inhibited from making large pitch maneuvers in the GBS.

Figure III-8 shows the velocity extrema on the approach resulting from both simulations for Pilot D. A run-to-run comparison revealed that V_{max} was larger in the airborne simulator, but that V_{min} was smaller (i.e., a larger negative speed deviation) in the ground-based simulator. This was

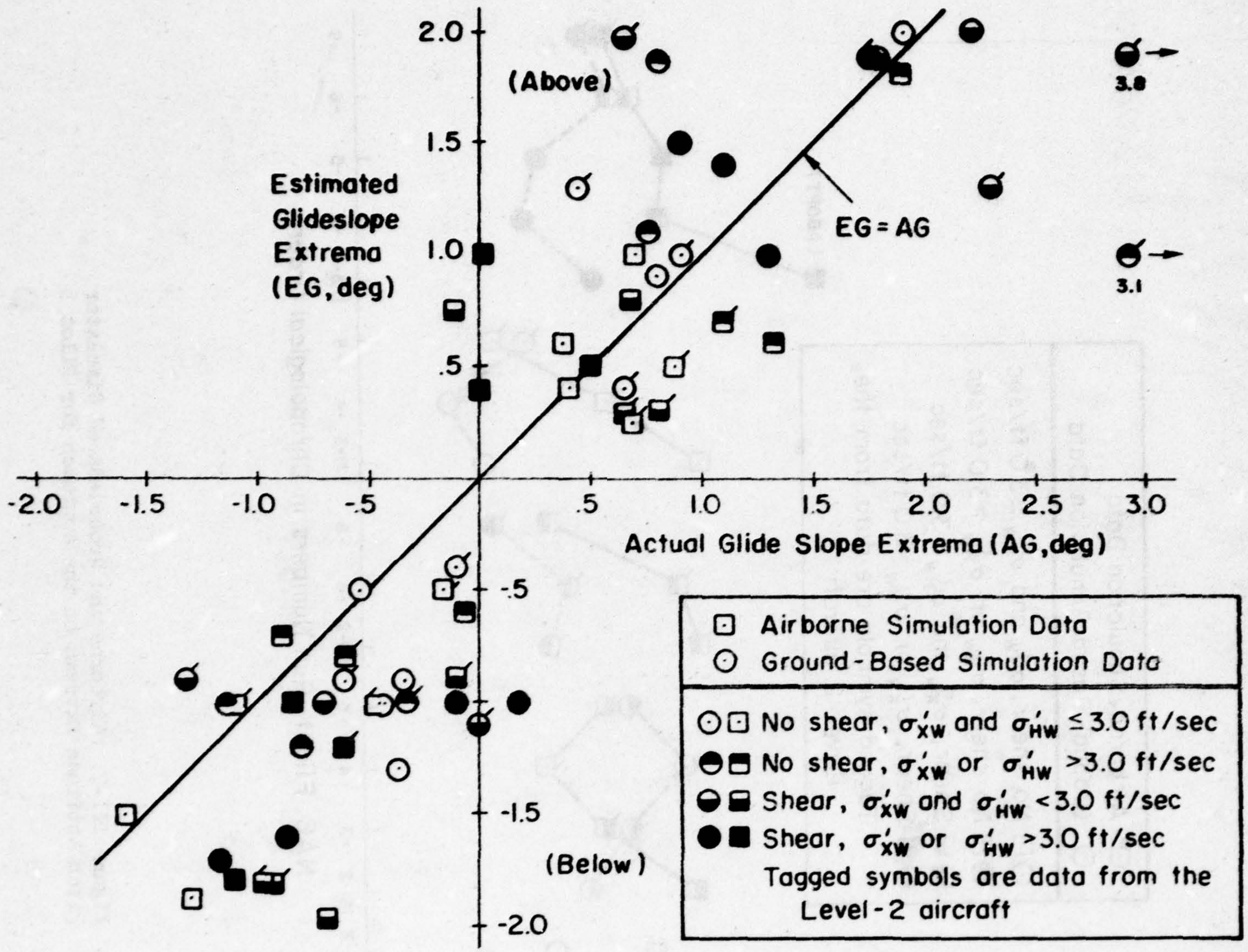


Figure III-6. Estimated Versus Actual Glide Slope Extrema on the Approach for Pilot D

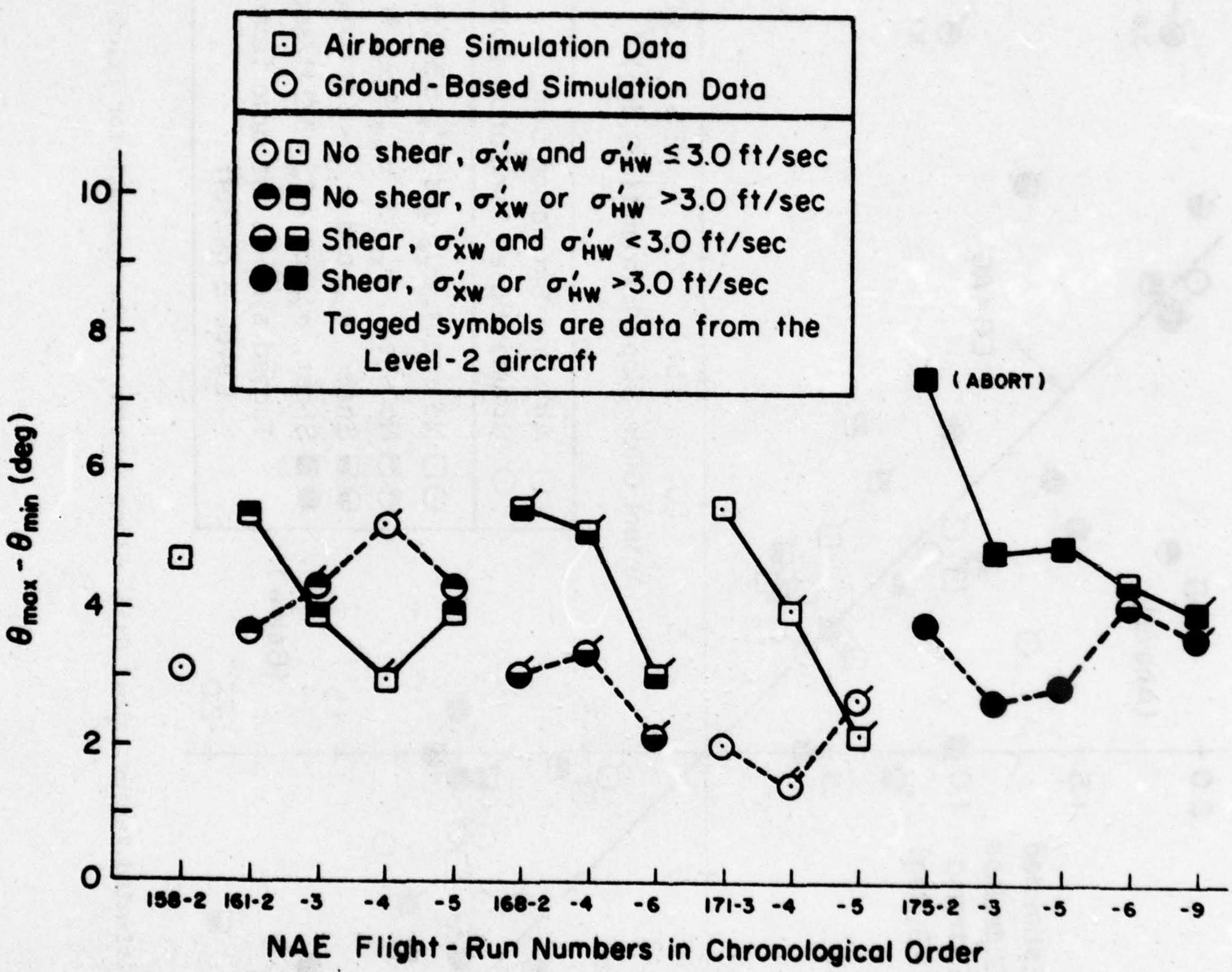


Figure III-7. Airborne and Ground-Based Simulator Pitch Attitude Extrema on the Approach for Pilot D

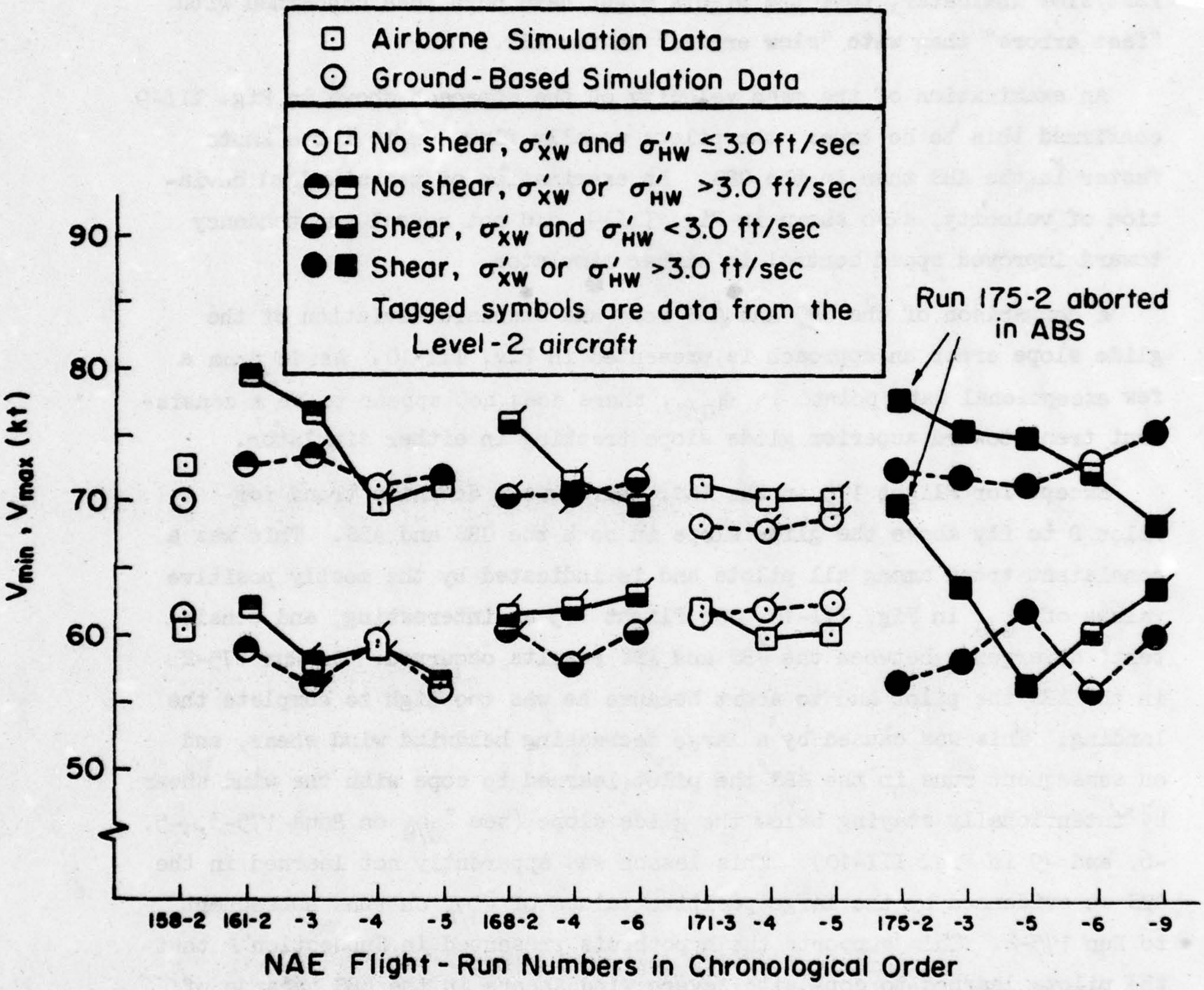


Figure III-8. Airborne and Ground-Based Simulator Velocity Extrema on the Approach for Pilot D

a consistent trend among all four subject pilots and implies that the pilots flew a few knots above the target airspeed of 65 kt in the airborne simulator, but not in the ground-based simulator. (Airspeed was displayed on a fast/slow indicator, thus the pilots might have been less concerned with "fast errors" than with "slow errors" in the ABS.)

An examination of the mean velocity on the approach shown in Fig. III-9 confirmed this to be true: the pilots usually flew two to three knots faster in the ABS than in the GBS. An examination of the standard deviation of velocity, also shown in Fig. III-9, did not reveal any tendency toward improved speed control in either simulator.

A comparison of the GBS and ABS mean and standard deviation of the glide slope error on approach is presented in Fig. III-10. Aside from a few exceptional data points in $\sigma\epsilon_{G/S}$, there does not appear to be a consistent trend toward superior glide slope tracking in either simulator.

Except for Flight 175 in the ABS, there was a definite trend for Pilot D to fly above the glide slope in both the GBS and ABS. This was a consistent trend among all pilots and is indicated by the mostly positive values of $\bar{\epsilon}_{G/S}$ in Fig. III-10. On Flight 175 an interesting, and consistent, divergence between the GBS and ABS results occurred. On Run 175-2 in the ABS the pilot had to abort because he was too high to complete the landing. This was caused by a large decreasing headwind wind shear, and on subsequent runs in the ABS the pilot learned to cope with the wind shear by intentionally staying below the glide slope (see $\bar{\epsilon}_{G/S}$ on Runs 175-3, -5, -6, and -9 in Fig. III-10). This lesson was apparently not learned in the GBS as evidenced by the large positive values of $\bar{\epsilon}_{G/S}$ on runs subsequent to Run 175-2. This supports the hypothesis presented in Subsection A that the pilots learned to cope with severe wind shears in the ABS because of repeated exposure to the same wind profile.

Note that the degraded glide slope performance for Runs 175-5, -6, and -9 in the GBS is consistent with the poorer handling quality ratings for these runs shown in Fig. III-1. This does not, however, appear to be a consistent trend, because there are many cases where degraded glide slope performance did not lead to degraded handling quality ratings.

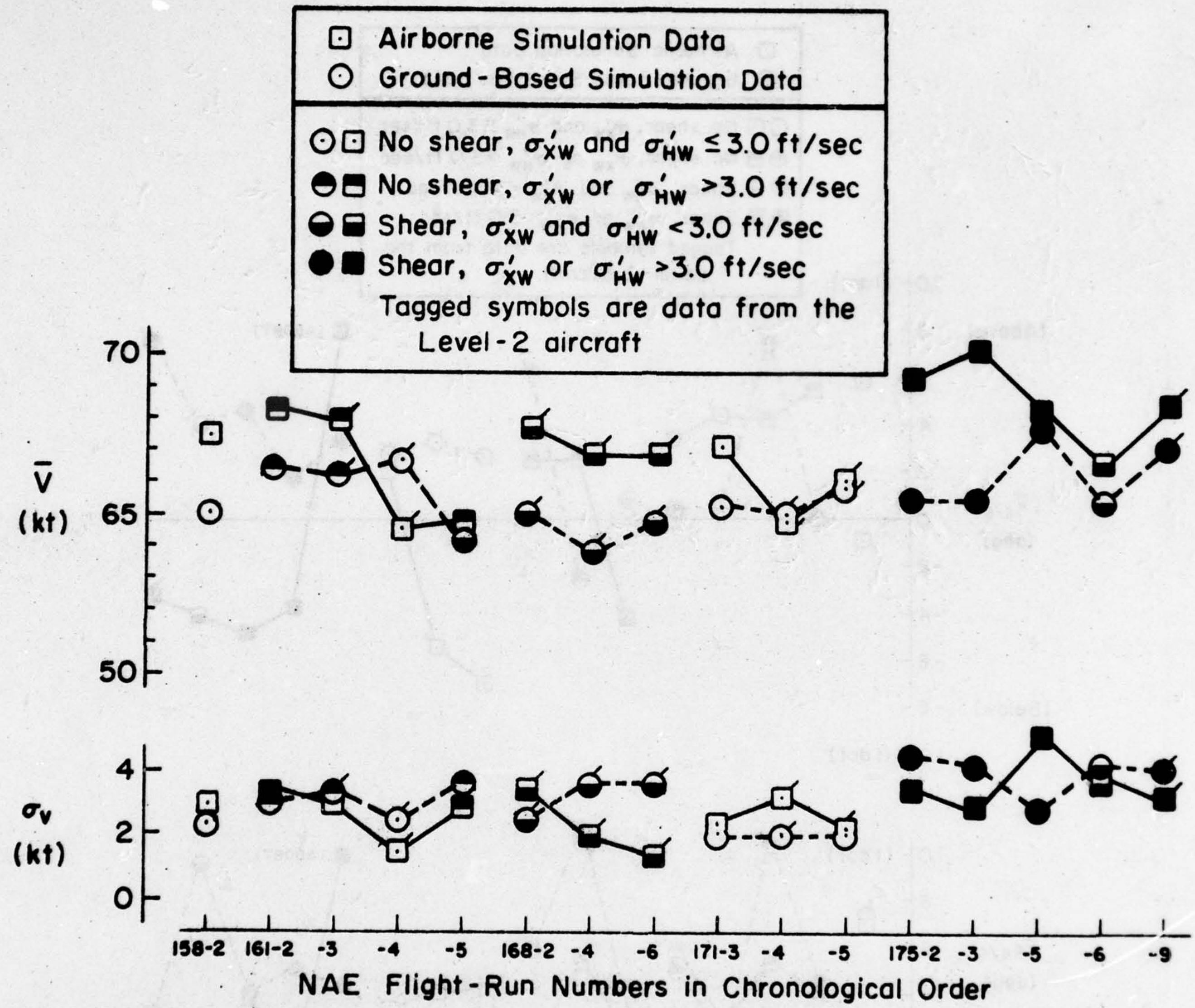


Figure III-9. Airborne and Ground-Based Simulator Mean and Standard Deviation of Velocity on the Approach for Pilot D

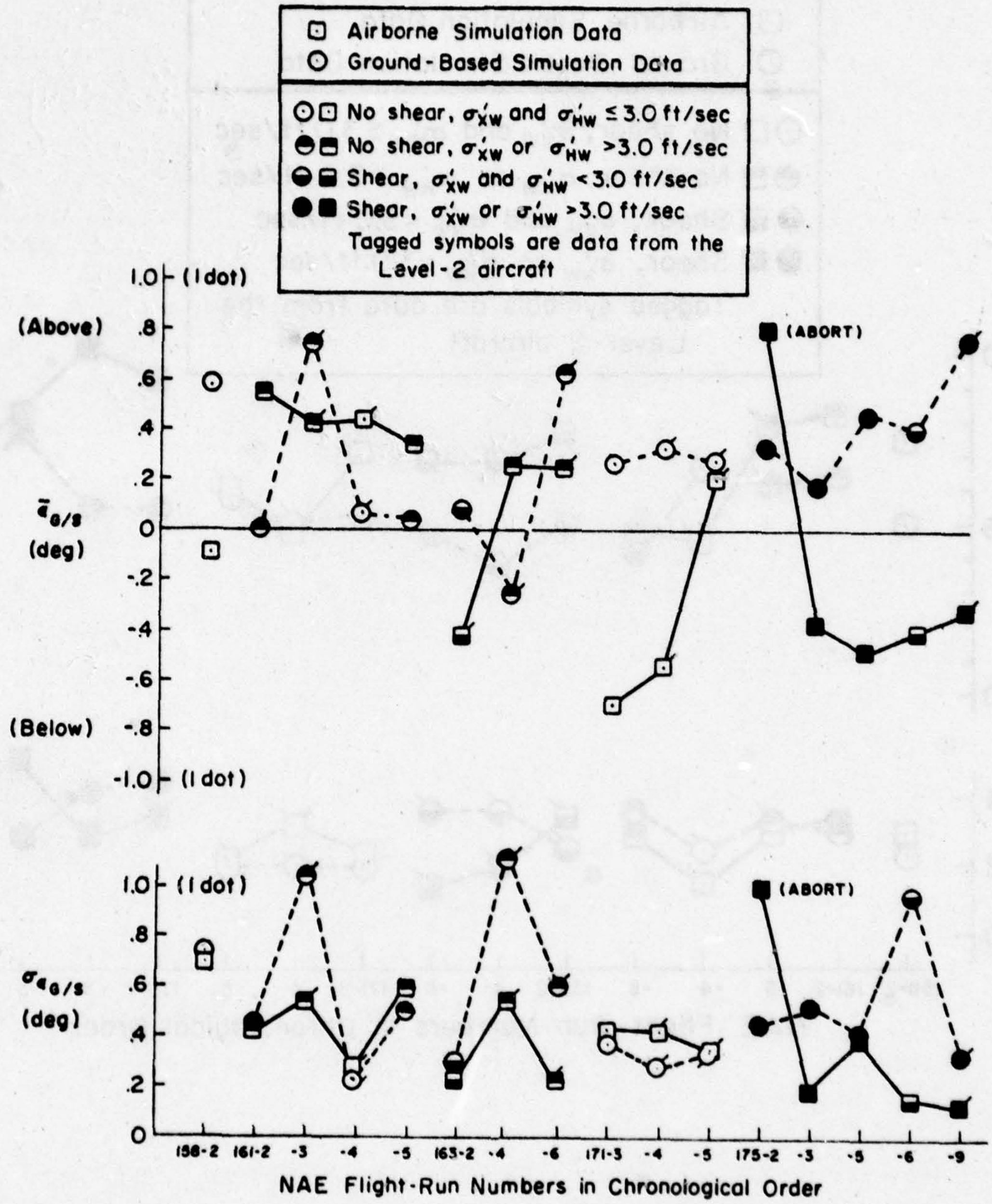


Figure III-10. Airborne and Ground-Based Simulator Mean and Standard Deviation of Glide Slope Error on the Approach for Pilot D

The change in the effective flight path angle required to stay on an inertial flight path angle of -6.0 deg for the wind conditions of Flight 175 is shown in the trim performance diagram of Fig. III-11. The effective flight path angle, γ_{eff}, is the aerodynamic flight path angle that must be flown in order to stay on the desired inertial flight path angle, γ_i. It can be seen from Fig. III-11 that staying below the glide slope is a good strategy because the effect of a decreasing headwind shear is to force the aircraft above the glide slope unless the pilot continuously decreases power. Also, unless the pilot recognizes the shear and responds appropriately, he will not have enough time to get re-established on the inertial flight path angle, and hence will be too high to land the aircraft.

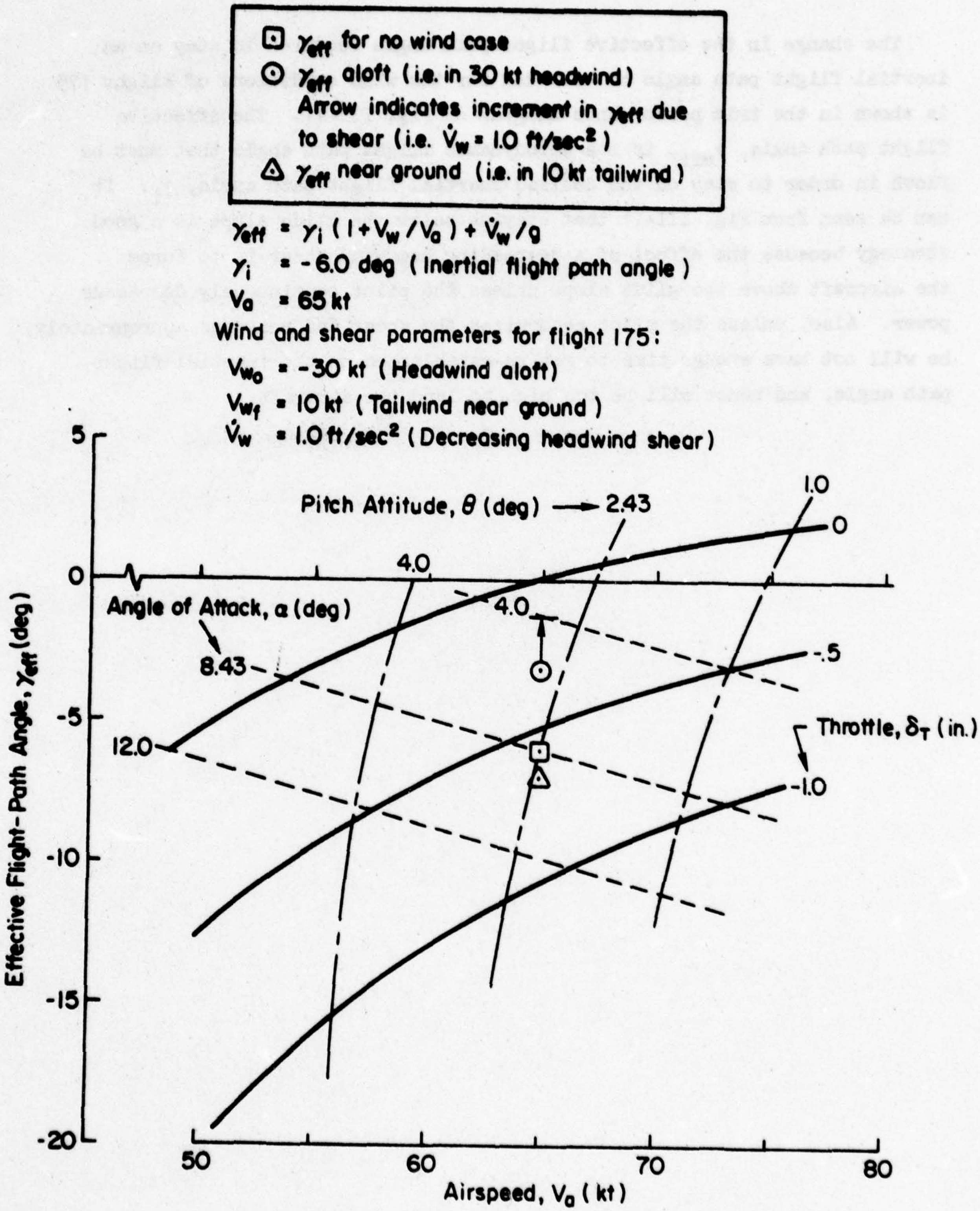


Figure III-11. Trim Performance Diagram for Level-6 Aircraft and Effective Flight Path Angles for Flight 175

SECTION IV

COMPARISON OF FLIGHT-RECORDED AND COMPUTER-GENERATED TURBULENCE RESULTS

This section compares the handling quality ratings and selected measures of pilot-vehicle performance data obtained with the flight-recorded turbulence (Task I) to the analogous data obtained with the Dryden model of computer-generated turbulence (Task II). The primary purpose for making this comparison is to determine how well the Dryden model represents naturally-occurring turbulence.

The results are compared using the rms level of the turbulence encountered along the IFR segment of the approach path as the independent variable. Differences in the results obtained are discussed and possible deficiencies in computer-generated turbulence models are presented. The data from runs using naturally-occurring atmospheric disturbances with large imbedded shears are identified in the presentation since these shears must be expected independently to influence both workload and performance.

The hybrid filtering technique described in Ref. 12 was used to partition the flight-recorded wind profiles into "low" and "high" frequency components. This was necessary in order to remove the "steady state" component prior to calculating the rms value of each high frequency component. The low-pass-filtered components were used to quantify the magnitude of the wind shear in the headwind and crosswind. The high-pass-filtered components were used to calculate the rms value of the headwind (σ'_{HW}), crosswind (σ'_{XW}), and downward (σ'_{DW}) components of the wind profile. A summary of the rms and wind shear parameters for each flight-recorded wind profile is contained in Ref. 12.

Wind profiles of the computer-generated turbulence were formed by adding constant headwind and crosswind components to the random turbulence generated by the Dryden model. Wind shears are sometimes modeled by summing the Dryden model turbulence with deterministic changes in the headwind and/or crosswind

(e.g., Ref. 19); however, this was not done for this investigation. Thus it was not necessary to filter the Dryden model wind profiles prior to computing the rms values of the wind components because the Dryden turbulence is a zero mean process over long periods of time. Not filtering the Dryden model turbulence did create a problem, though.

A theoretical correction factor to account for the filtering process could be computed based on the characteristics of the high-pass filter described in Ref. 12 and the shaping filters of the Dryden model (Ref. 5). This correction factor could then be used to adjust the unfiltered rms deviations of the Dryden model wind profiles, and thus to make direct comparisons of the Task I and Task II results. There are complications in doing this, however. In particular the correction factor is a function of aircraft airspeed and altitude, and is applicable only over an infinite sample interval in time (i.e., not over the finite sample interval used to measure the rms deviation during the IFR portion of the approach). The results reported in Ref. 13 demonstrate that the rms values of Dryden model turbulence measured over short time intervals can be quite different from the "steady state" values of the rms. Thus it would be inappropriate to apply one correction factor to all of the Task II runs. It is appropriate, however, to compare the trends of the results obtained from Task I to those from Task II, and this is done below.

The data for a different evaluation pilot is presented in this section because Pilot D failed to provide Cooper-Harper ratings for most of his Task II runs. The data for the pilot presented herein is representative of the data for the other evaluation pilots.

A. COOPER-HARPER RATINGS

Figure IV-1 shows the Cooper-Harper ratings for the IFR segment of the approach versus the along-track rms turbulence level, σ'_{HW}, for Pilot C. The flight-recorded turbulence data (Task I) and the computer-generated turbulence data (Task II) are indicated by circles and squares, respectively, with the solid data points representing Task I runs having "significant" wind shears. The tagged data points are runs using the Level-2 aircraft,

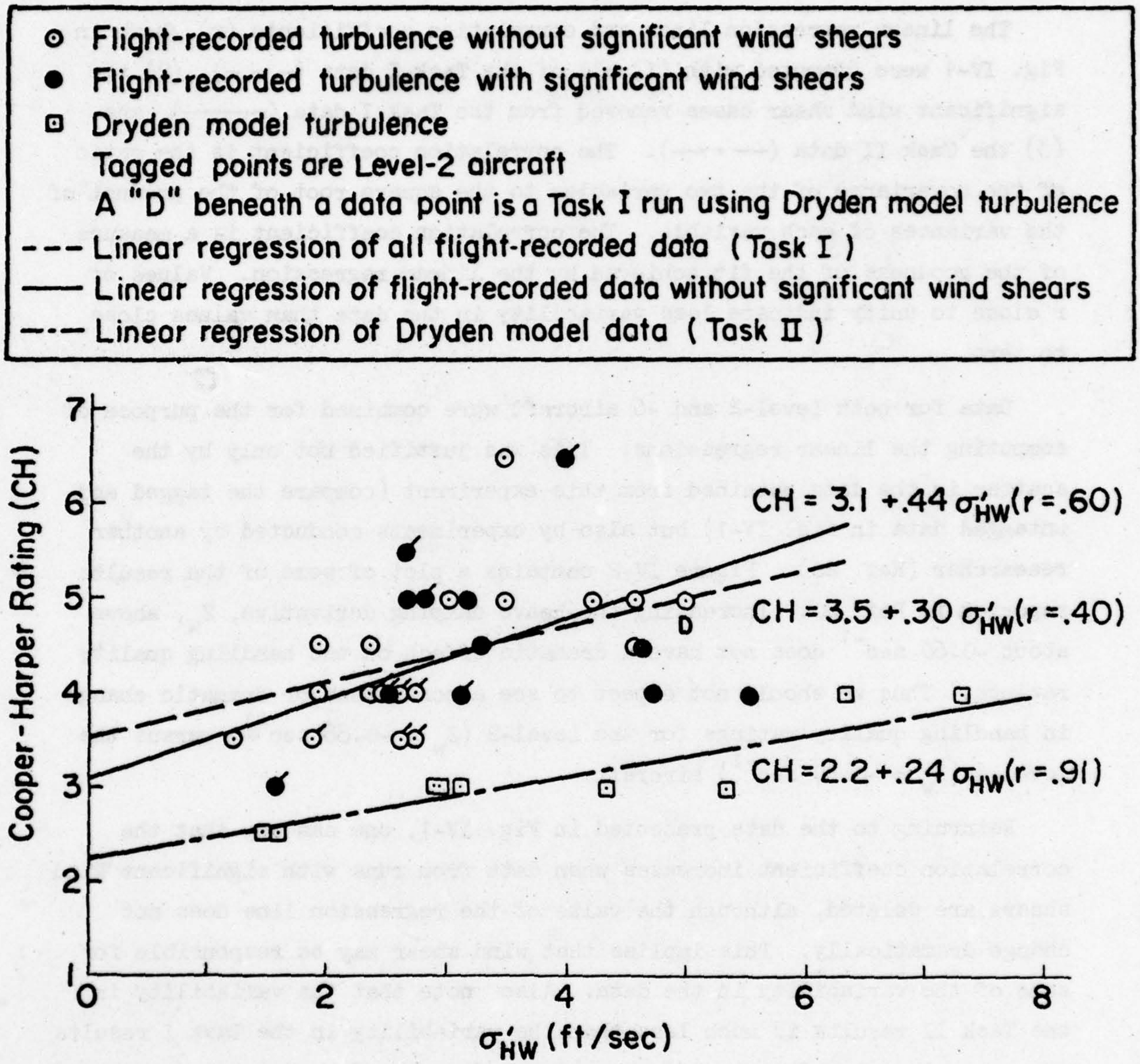


Figure IV-1. Flight-Recorded and Computer-Generated Turbulence IFR Cooper-Harper Ratings for Pilot C

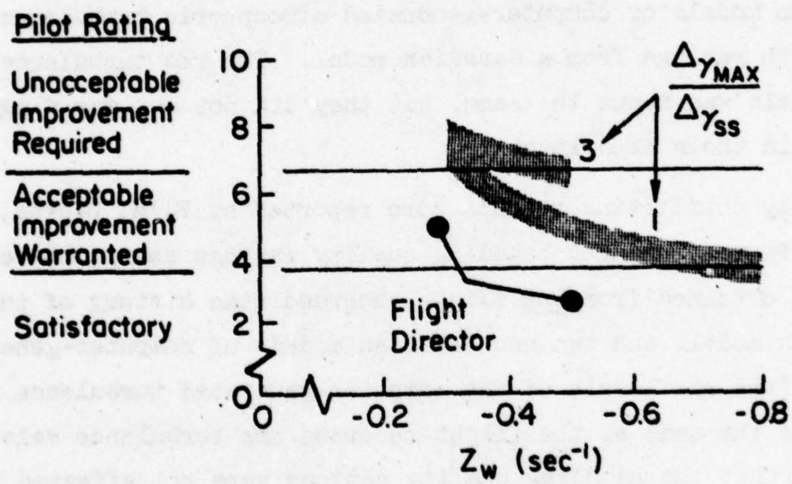
and the letter "D" below a data point indicates a Task I run using Dryden model turbulence.

The linear regression lines and correlation coefficients (r) shown in Fig. IV-1 were computed with (1) all of the Task I data (– – –), (2) the significant wind shear cases removed from the Task I data (———), and (3) the Task II data (—•—). The correlation coefficient is the ratio of the covariance of the two variables to the square root of the product of the variances of each variable. The correlation coefficient is a measure of the goodness of the fit achieved by the linear regression. Values of r close to unity indicate less variability in the data than values close to zero.

Data for both Level-2 and -6 aircraft were combined for the purpose of computing the linear regressions. This was justified not only by the scatter in the data obtained from this experiment (compare the tagged and untagged data in Fig. IV-1) but also by experiments conducted by another researcher (Ref. 20). Figure IV-2 contains a plot of some of the results reported in Ref. 20. Increasing the heave damping derivative, Z_w, above about $-0.60\ sec^{-1}$ does not have a dramatic effect on the handling quality ratings. Thus we should not expect to see a consistent or dramatic change in handling quality ratings for the Level-2 ($Z_w = -0.88\ sec^{-1}$) versus the Level-6 ($Z_w = -0.57\ sec^{-1}$) aircraft.

Returning to the data presented in Fig. IV-1, one can see that the correlation coefficient increases when data from runs with significant wind shears are deleted, although the value of the regression line does not change dramatically. This implies that wind shear may be responsible for some of the variability in the data. Also note that the variability in the Task II results is much less than the variability in the Task I results even when the significant wind shear cases from the Task I data are removed. An hypothesis for this higher variability is presented and discussed in Subsection IV.C.

In addition, the ordinate intercepts shown in Fig. IV-1, which reflect the Cooper-Harper rating for calm air, are numerically higher in the Task I results. Thus it appears that the handling qualities obtained with the flight-recorded wind profiles are inferior to those obtained with the Dryden



Note: Adopted from Ref. 20.

Figure IV-2. Effect of the Heave Damping Derivative on Handling Quality Ratings

model of computer-generated turbulence. An exception to this result is provided by the sole Dryden model turbulence run that was intermingled with the Task I runs for Pilot C (see the data point identified with a "D" in Fig. IV-1). However, the Cooper-Harper ratings for the Task I Dryden model turbulence runs for the other three pilots were always 1 to 1.5 rating points below the Task I regression lines. Thus, in general, these data support the hypothesis that Dryden model turbulence can yield overly optimistic pilot opinion ratings.

Similar results were reported by Jacobson and Joshi (Refs. 14 and 15). They reported that different handling quality ratings were obtained from non-Gaussian models of computer-generated atmospheric turbulence when compared with ratings from a Gaussian model. The rms turbulence level for all the models was about the same, but they did not use any flight-recorded turbulence in their experiments.

Partially conflicting results were reported by P. M. Reeves, et al (Ref. 7). Reeves compared handling quality ratings and pilot-vehicle performance obtained from one flight-recorded time history of turbulence, one Gaussian model, and two non-Gaussian models of computer-generated turbulence (the rms levels of the computer-generated turbulence were all scaled to be the same as the flight-recorded rms turbulence velocity). He reported that the handling quality ratings were not affected by the different turbulence sources, but that pilot-vehicle performance was poorest for the flight-recorded turbulence. Pilot-vehicle performance for all the computer-generated turbulence models was similar.

There were some interesting similarities in the Cooper-Harper ratings obtained from all four pilots when plotted as in Fig. IV-1. For example, the intercepts of the regression lines at the ordinate are in good agreement, being at a Cooper-Harper rating of between 3 and 4 for all pilots. The handling qualities of the aircraft would therefore have either "Some mildly unpleasant deficiencies" or "Minor but annoying deficiencies," even in the absence of atmospheric disturbances. Also, the slopes of the linear regression lines were quite similar, which indicates that the gradient of handling quality degradation due to atmospheric disturbance was about the same for all pilots.

B. PILOT-VEHICLE TRACKING PERFORMANCE

Figures IV-3 and IV-4 present plots of the IFR pitch attitude and airspeed extrema, respectively, plotted versus the rms high-pass-filtered along-track wind component, σ'_{HW}. The figures include the raw data, linear regressions, and correlation coefficients from both the Task I and Task II experiments.

In Figs. IV-3 and IV-4 the regression lines and correlation coefficients are shown for all the Task I data and with the significant wind shear runs removed. In many instances the correlation coefficients are improved (i.e., increased) after the significant wind shear runs are removed. This indicates that some of the variability in the data is due to the wind shears. However, there are many other instances where the correlation coefficients are either unchanged or actually reduced after the significant shear runs are removed. (This is true not only for the pilot whose data is presented in this section but for all of the other pilots as well.) This indicates that there are properties of the flight-recorded wind profiles other than wind shears responsible for the variability in the data.

Note that the data from the Dryden model runs intermingled with the Task I runs are shown in Figs. IV-3 and IV-4 and are labeled by the letter "D." These data almost invariably lie below the Task I regression lines, which indicates that the performance degradation obtained from the Dryden model is not as severe as that obtained with the flight-recorded wind profiles. Figures IV-3 and IV-4 also show, for the purpose of comparison, the Task II regression lines for the Dryden model of computer-generated turbulence. Not only are the pilot-vehicle performance degradations different (as discussed above it is difficult to compare the absolute values of the results of Tasks I and II because of the filtering required to extract the rms turbulence levels from the Task I wind profiles), but the variability in the Task I data is much higher than in the Task II data. This is consistent with the subjective results presented in the previous subsection.

The relatively high correlation coefficients obtained with the Dryden model of computer-generated turbulence were not surprising. Indeed, these

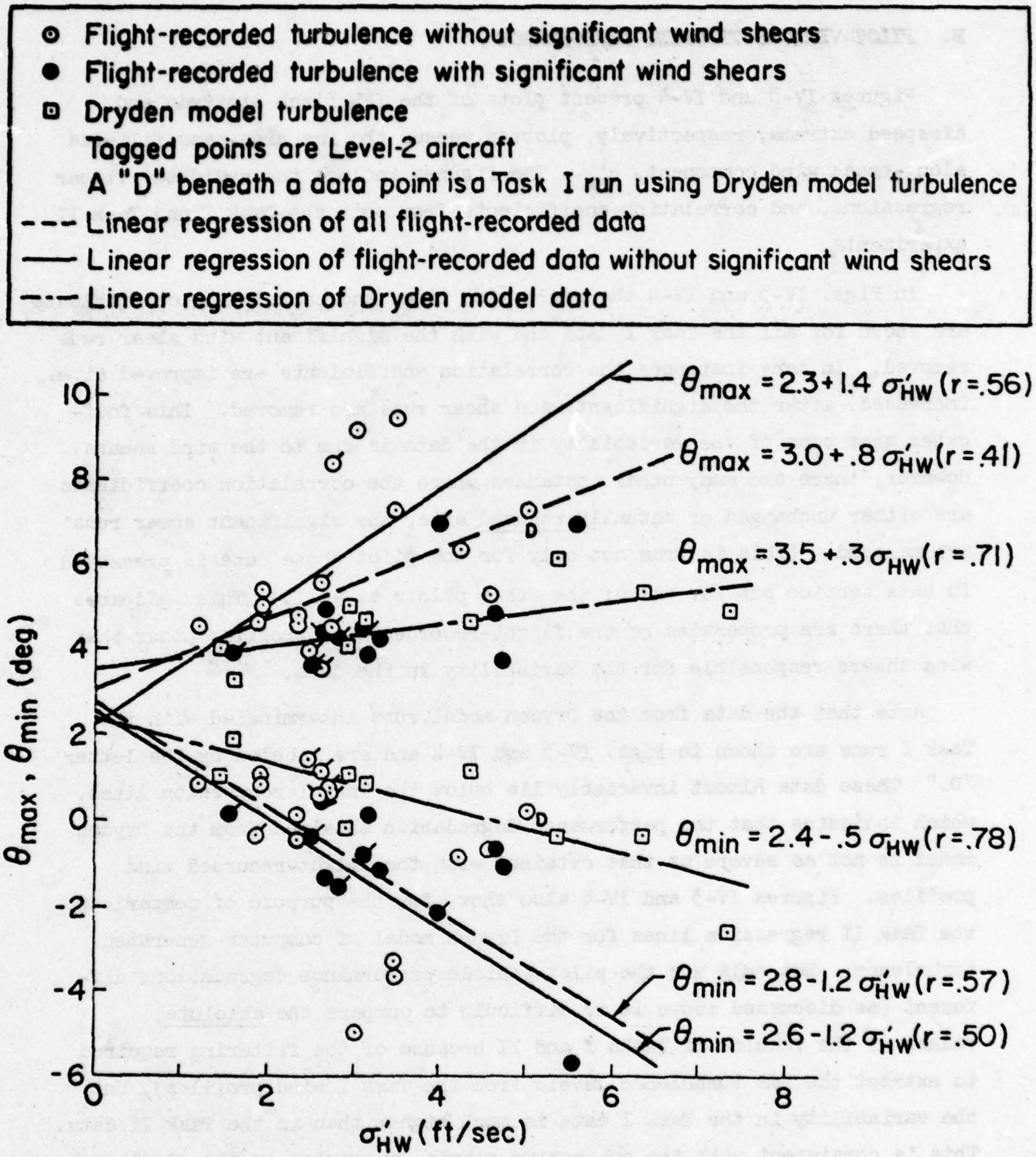


Figure IV-3. Flight-Recorded and Computer-Generated Turbulence Pitch Attitude Extrema on the Approach

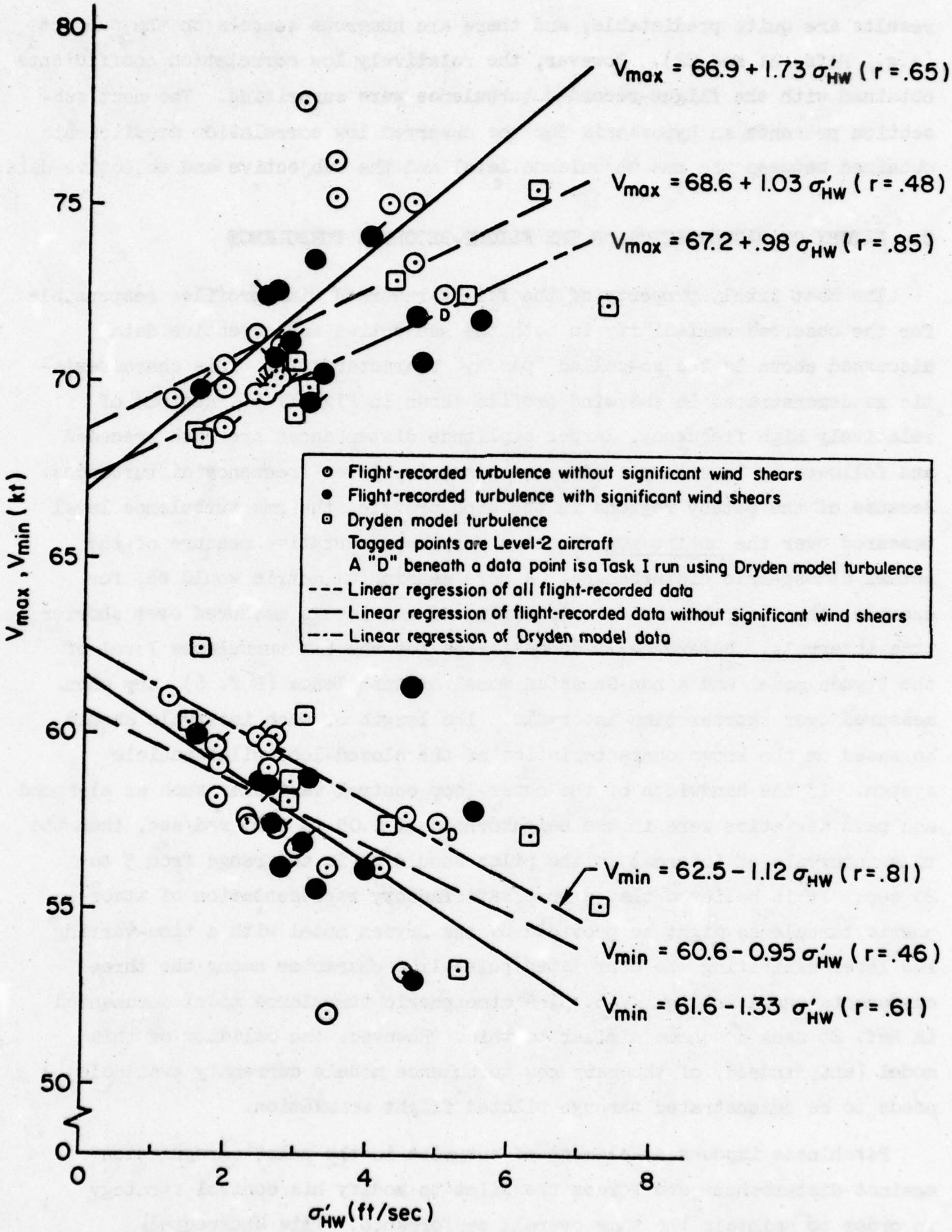


Figure IV-4. Flight-Recorded and Computer-Generated Turbulence Velocity Extrema on the Approach

results are quite predictable, and there are numerous sources on the subject (e.g., Refs. 21 and 22). However, the relatively low correlation coefficients obtained with the flight-recorded turbulence were surprising. The next subsection presents an hypothesis for the observed low correlation coefficients obtained between the rms turbulence level and the subjective and objective data.

C. PATCHY CHARACTERISTICS OF THE FLIGHT-RECORDED TURBULENCE

The most likely property of the flight-recorded wind profiles responsible for the observed variability in both the subjective and objective data discussed above is the so-called "patchy" characteristic. This characteristic is demonstrated in the wind profile shown in Fig. IV-5. Regions of relatively high frequency, larger amplitude disturbances are both preceded and followed by lower amplitude, and possibly, lower frequency disturbances. Because of the patchy regions in the wind profile, the rms turbulence level measured over the entire run is not a very representative measure of the actual atmospheric disturbances. A more meaningful metric would be, for example, the distribution (or histogram) of rms levels measured over shorter time intervals. Reference 13 demonstrates how the rms turbulence level of the Dryden model and a non-Gaussian model of turbulence (Ref. 6) vary when measured over shorter time intervals. The length of such intervals should be based on the known characteristics of the closed-loop pilot-vehicle system. If the bandwidth of the outer-loop control variables such as airspeed and path deviation were in the neighborhood of 0.05 to 0.20 rad/sec, then the time intervals of interest to the pilot should be in the range from 5 to 20 sec. It is believed that a more satisfactory representation of atmospheric turbulence might be provided by the Dryden model with a time-varying rms level exhibiting the correlated pulse-like character among the three components shown in Fig. IV-5. The atmospheric turbulence model documented in Ref. 23 uses a scheme similar to this. However, the validity of this model (and, indeed, of the many new turbulence models currently available) needs to be demonstrated through piloted flight simulation.

Patchiness imposes an element of surprise in the pilot's regulation against disturbances and forces the pilot to modify his control strategy in order to maintain the same overall performance. This unexpected

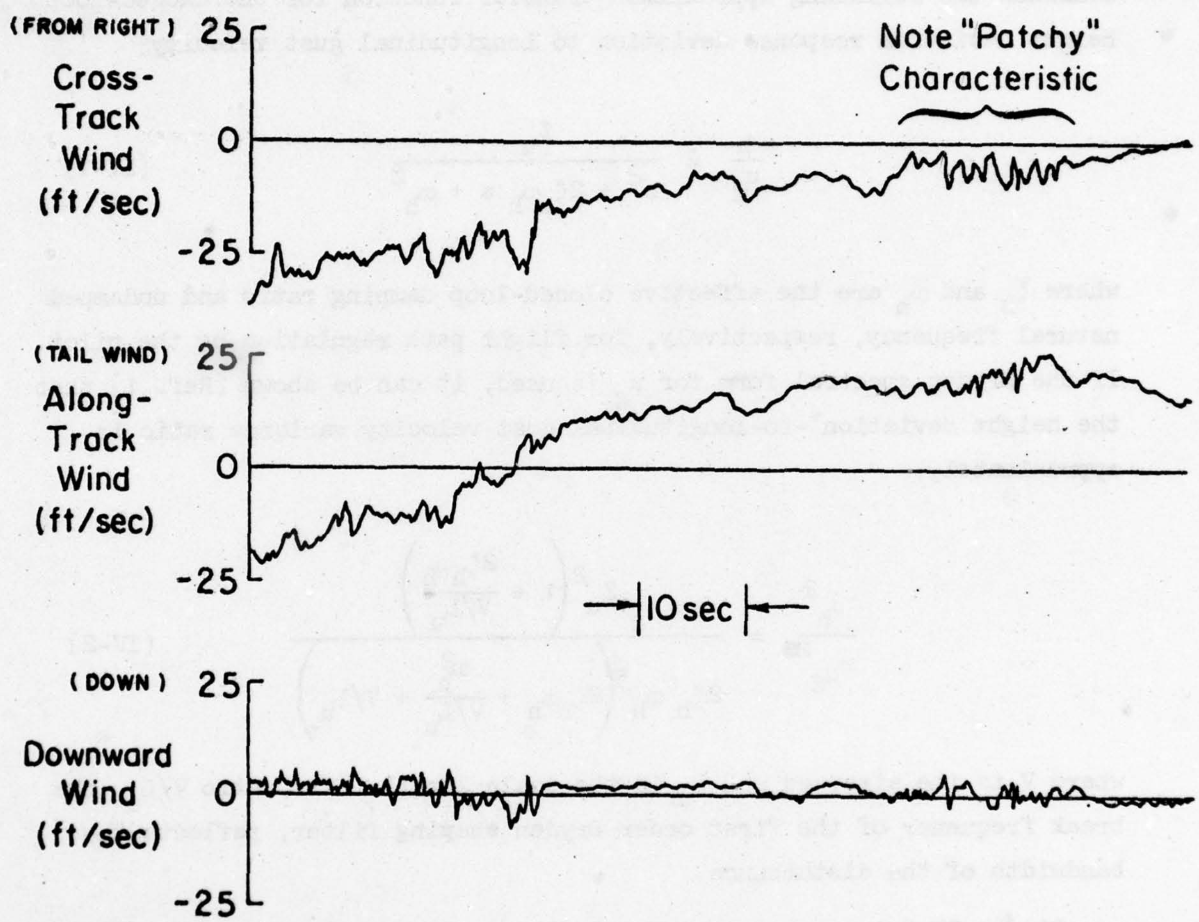


Figure IV-5. Flight-Recorded Wind Profile Demonstrating Patchy Characteristic of Turbulence

readaptation of control strategy is viewed as additional workload which leads to inferior pilot rating as well as inferior pilot-vehicle performance.

To demonstrate how the pilot maintains the same overall performance, consider the following approximate transfer function for the closed-loop height deviation response deviation to longitudinal gust velocity:

$$\frac{h}{u_g} \doteq \frac{Z_u}{s^2 + 2\zeta_h\omega_h s + \omega_h^2} \qquad \text{(IV-1)}$$

where ζ_h and ω_h are the effective closed-loop damping ratio and undamped natural frequency, respectively, for flight path regulation by the pilot. If the Dryden spectral form for u_g is used, it can be shown (Ref. 1) that the height deviation*-to-longitudinal gust velocity variance ratio is approximately:

$$\frac{\sigma_h^2}{\sigma_{u_g}^2} = \frac{Z_u^2\left(1 + \frac{2\zeta_h\omega_h}{V/L_u}\right)}{2\zeta_h\,\omega_h^3\left(2\zeta_h\omega_h + \frac{\omega_h^2}{V/L_u} + V/L_u\right)} \qquad \text{(IV-2)}$$

where V is the airspeed and L_u is the scale length. The ratio V/L_u, the break frequency of the first order Dryden shaping filter, reflects the bandwidth of the disturbance.

Figure IV-6 is a plot of the ratio σ_h/σ_{u_g} versus V/L_u for the test aircraft's value of Z_u, one value of ζ_h and two values of ω_h. For the aircraft investigated, the pilot can increase ω_h by increasing the gain in his throttle displacement response to his perceived height deviation. The indicated values of ω_h would correspond to "moderate" and "tight" throttle-to-height loop closures. The effective damping ratio, ζ_h, was

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* "Height deviation" here is synonomous with "flight path deviation" in Fig. IV-6.

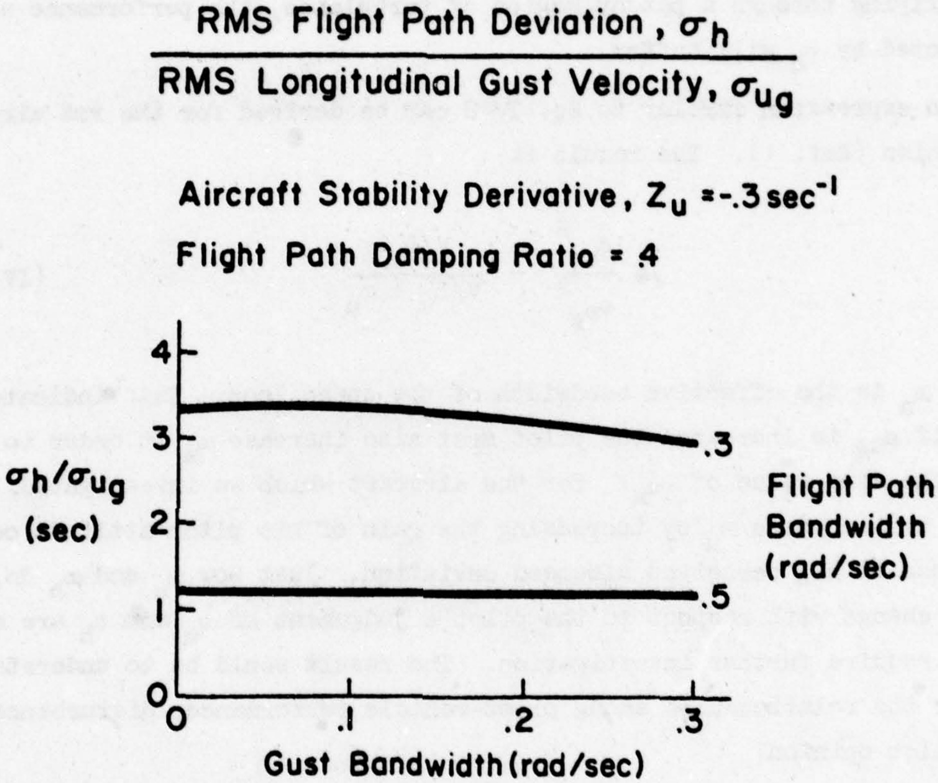

Figure IV-6. RMS Flight Path Deviation as a Function of RMS Longitudinal Gust, Bandwidth of the Gust Velocity, and Bandwidth of the Flight Path Control Loop

held constant because the pilot would close a tighter loop only if he could maintain an adequate phase margin.

Figure IV-6 shows that σ_h/σ_{u_g} does not change much with the bandwidth of the gust velocity but changes more dramatically with the bandwidth of the flight path loop. Thus if the pilot does not immediately increase ω_h when flying through a patchy region of turbulence, the performance as reflected by σ_h will suffer.

An expression similar to Eq. IV-2 can be derived for the rms airspeed deviation (Ref. 1). The result is:

$$\frac{\sigma_{u_a}^{\,2}}{\sigma_{u_g}^{\,2}} = \frac{V/L_u}{V/L_u + \omega_u} \qquad \text{(IV-3)}$$

where ω_u is the effective bandwidth of the speed loop. This indicates that if σ_{u_g} is increased the pilot must also increase ω_u in order to maintain the same value of σ_{u_a}. For the aircraft which we investigated, the pilot can increase ω_u by increasing the gain of his pitch attitude control response to his perceived airspeed deviation. Just how ω_u and ω_h do, in fact, change with respect to the pilot's judgement of σ_u and σ_h are matters which require further investigation. The result would be to understand better the relationships among pilot-vehicle performance, disturbance levels, and pilot opinion.

D. SUBJECTIVE RATINGS OF TURBULENCE REALISM AND PATCHINESS

During the Task II experiments the pilots were requested to rate the realism and to judge the patchy characteristics of the computer-generated turbulence. The histograms presented in Fig. IV-7 summarize the resulting data.

The histograms are separated into groups of turbulence realism ratings of "Good" or "Very Good" and "Fair" or "Poor." The results indicate that virtually all runs in which the turbulence realism was rated "Good" to "Very Good" are runs in which the patchiness of the turbulence was judged "About Right," that is, not "Too Continuous" or not "Too Patchy." Runs in

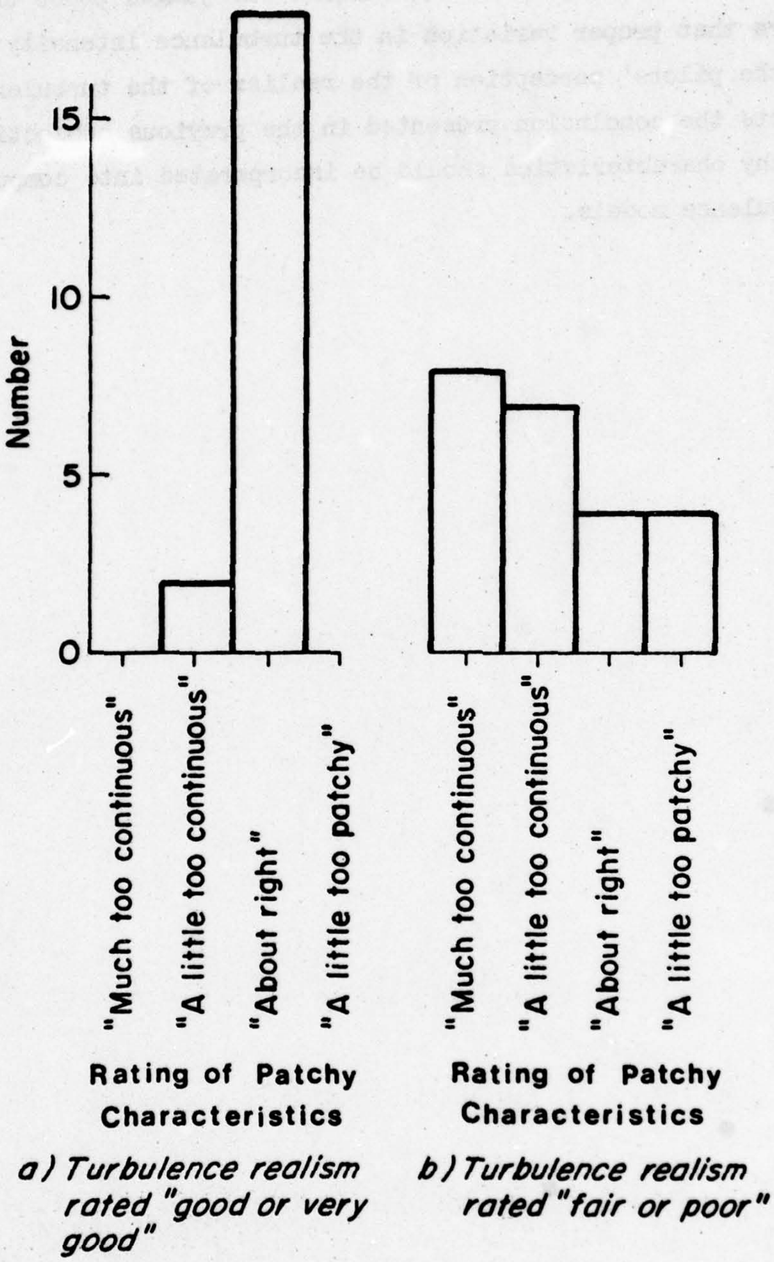

Figure IV-7. Histograms of Patchy Characteristic Rating for (a) "Good or Very Good" and (b) "Fair or Poor" Turbulence Realism Ratings for all Task II Data

which the turbulence realism was rated "Fair" to "Poor" were nearly always runs in which the continuity of the turbulence was judged to be unrealistic. Thus it appears that proper variation in the turbulence intensity is very important to the pilots' perception of the realism of the turbulence. This finding supports the conclusion presented in the previous subsection that realistic patchy characteristics should be incorporated into computer-generated turbulence models.

SECTION V
CONCLUSIONS

The conclusions presented below are based upon the results of an airborne and ground-based piloted simulation investigation of powered-lift aircraft handling qualities degradation due to naturally-occurring and computer-generated atmospheric turbulence. These results include pilot commentary regarding the fidelity of the ground-based simulator (GBS) and its comparison to the airborne simulator (ABS), as well as subjective and objective data resulting from the two simulations. Whenever possible the conclusions are made in light of the overall program objectives delineated in Section I.

A. PILOTS' SUBJECTIVE IMPRESSIONS OF THE AIRBORNE AND GROUND-BASED SIMULATORS

In general all four of the subject pilots regarded the ground-based simulator fidelity to be acceptable and claimed that the performance and control of the simulated powered-lift aircraft in the ground-based simulator were very representative of the airborne simulator. There were, however, differences between the two simulators, and the pilots were prompted to comment on the differences that they considered to be important.

The most common and probably the most important complaint was the lack of good visual cues in the ground-based simulator during the VFR and flare segments of the approach. On the other hand, all the pilots commented that the instrumentation in the ground-based simulator was superior to that in the airborne simulator, and that the "breakout" (i.e., the transition from IFR to VFR) was more realistic in the ground-based simulator, because a hood had to be removed in the airborne simulator. Section II contains a more detailed description of the pilot commentary and discussion of differences in the two simulators.

Taken together the pilot commentary provides a qualitative basis for addressing one of the overall program objectives: to determine the degree to which the airborne simulator experiment could be transferred to and its results duplicated on a modern ground-based simulator with six-degrees-of-freedom in motion and a colored visual display. The conclusion is that most characteristics of an airborne simulator can be reproduced on a modern ground-based simulator, but that the visual cues presented in this particular ground-based simulator were deficient. Thus a comparison between the ground-based and airborne simulator IFR results can be made confidently, whereas a comparison of VFR and flare results should be made circumspectly.

Reference 24 is a good source on the practical use of modern ground-based simulators and their advantages and disadvantages with respect to flight testing. Much work is currently being done to overcome some disadvantages by improving the fidelity of visual simulators. Reference 25 summarizes some of the work currently being done in the field of visual simulators (as well as simulators in general) and presents forecasts of what to expect in the future.

B. COMPARISON OF AIRBORNE AND GROUND-BASED SIMULATOR RESULTS

The Cooper-Harper handling quality ratings and some selected pilot-vehicle performance measures obtained in the NAE Airborne V/STOL Simulator were compared to the analogous data obtained in the FSAA ground-based simulator. These data were obtained under a variety of atmospheric conditions and thus document the handling qualities degradation due to atmospheric disturbances as well as the difference between data obtained in an airborne versus a ground-based simulator. The atmospheric disturbances included light and moderate to heavy turbulence, as well as large wind shears.

1. Cooper-Harper Ratings

A run-to-run comparison of the ABS and GBS Cooper-Harper ratings revealed that the differences in the majority of the data were equal to or less than one half of a rating point. This was not surprising, however, because variations within either the ABS or GBS ratings were very often

equal to or greater than one half of a rating point, even when the disturbance was effectively unchanged (i.e., on the same flight). Cooper-Harper rating differences this small probably represent the uncertainty in the pilots' estimates of the handling qualities of a particular aircraft.

The runs with larger differences in the Cooper-Harper ratings (one or more rating points) were generally runs in which wind shear was present. Thus flying through wind profiles that contained wind shears introduced a greater share of the variability in the ratings than flying through wind profiles containing only calm air or turbulence. An explanation for this finding is presented below.

There were no consistent trends for superior or inferior ratings in the ABS versus the GBS. There were, however, definite learning trends present in the ABS ratings that were not present in the GBS ratings, especially for runs that contained wind shear. The inference is that the pilots learned to "fly the disturbance" in the ABS, but not in the GBS.

The necessarily different scenarios in the two simulators and the differences in experimental protocols probably caused this difference in learning trends between the ABS and GBS handling quality ratings. In the ABS the pilots were exposed to the atmospheric conditions as the safety pilot flew the aircraft to its initial position. Also, because there were only five to ten minutes between flights in the ABS, the pilot knew that the atmospheric disturbances on the next run would be essentially unchanged from the previous evaluation flight. This was particularly important on days when wind shears were present, because the pilot could develop the proper control strategy for coping with the wind shear after repeated exposure to essentially the same wind profile.

Although the pilots were exposed to the same wind profiles and in the same chronological order in the GBS as they were in the ABS, the pilots treated each run in the GBS as a new wind profile. In addition, in the GBS the digital computer simply puts the "aircraft" at its initial condition (as opposed to flying it there), thus retaining an element of surprise.

If the pilots had been informed that the atmospheric conditions on subsequent evaluation flights in the GBS were very similar to those on

their first flight (i.e., if there had been an attempt to duplicate the ABS scenario) then a closer correspondence between the ABS and GBS handling quality ratings might have been obtained. However, this would not have been very realistic in another sense, because an operational pilot is customarily exposed to the atmospheric conditions on the final approach only once, unless he is forced to perform a go-around.

2. Pilot Ratings of Task Difficulty Due to Wind Shear and Turbulence

The pilot ratings of task difficulty due to wind shear and turbulence were cross-plotted with the Cooper-Harper handling quality ratings. A comparison of the ABS and GBS data revealed that the pilots perceived the influence of atmospheric disturbances and assigned handling quality ratings in the airborne and ground-based simulators in a similar manner. Also, runs that contained wind shear and turbulence were in general perceived as being more difficult and rated poorer in both simulators.

3. Estimated Pilot-Vehicle Tracking Performance

The pilots were required to estimate their maximum airspeed and glide slope errors on the approach in both simulators. A comparison of the estimated and actual airspeed errors revealed that the pilots consistently underestimated the actual airspeed errors in both simulators (i.e., pilot said +5 kt when he was really +10 kt). There was a tendency toward better airspeed estimates in the GBS.

A comparison of the estimated and actual glide slope errors revealed that the pilots were not able to assess accurately their glide slope performance in either the airborne or ground-based simulator.

4. Actual Pilot-Vehicle Tracking Performance

A comparison of the ABS and GBS pitch attitude extrema on the approach revealed that the pitch attitude excursions in the ABS were consistently larger than those in the GBS. One possible explanation for this phenomenon is the difference in the graduation of pitch attitude on the ADIs in the

two simulators (1 deg increments in the FSAA versus 5 deg increments in the NAE Airborne V/STOL Simulator). Other possible explanations are that the pilots used a different control technique in the ABS versus the GBS, or that the pilots were inhibited from making large pitch maneuvers in the GBS.

A comparison of the mean airspeed on the approach revealed that the pilots usually flew 2 to 3 kt faster in the ABS than they did in the GBS. An examination of the standard deviation of airspeed did not reveal any tendency toward improved speed control in either simulator.

An examination of the mean glide slope error on the approach revealed a tendency for the pilots to stay above the glide slope in both the ABS and GBS. An exception to this trend existed in the ABS data for runs that contained wind shear. The pilots learned to cope with large decreasing headwind shears by staying below the glide slope in the ABS but did not adopt this strategy in the GBS. This finding supports the hypothesis presented above that the pilots learned to cope with severe wind shears in the ABS because of repeated exposure to essentially the same wind profile, whereas in the GBS the pilots were not aware of the sequential repetition of similar atmospheric conditions.

3. Summary of Findings

The following items summarize the findings discussed above and in Section III:

a. The handling quality ratings obtained in both the airborne and ground-based simulators were similar.

b. The first handling quality rating for a particular set of atmospheric conditions is usually the worst.

c. Learning trends existed in the airborne simulator results that were not present in the ground-based simulator results.

d. There were definite differences in the combined pilot-vehicle error performance data obtained in the two simulators.

e. Wind shear was responsible for a greater share of the variability than turbulence in comparing the handling quality ratings between the ground-based and airborne simulators.

Item a is important because it has been the tacit assumption used to justify the wide-spread use of ground-based simulators. Item b suggests that ground-based simulators could be used for training pilots to cope with extreme atmospheric conditions. Specifically, a scheme for rating the severity of the atmospheric conditions could be developed (e.g., frontal-type wind shears, moderate decreasing headwind shear, heavy turbulence), and pilots could be trained to cope with the various atmospheric conditions in a particular aircraft. Such rating schemes could easily be developed and evaluated in a ground-based simulator.

Item c has a potential impact on the procedures used to conduct and to interpret the results from both airborne and ground-based simulation experiments. Specifically, overly optimistic results from an airborne simulation can be inferred if the effects of learning are not properly accounted for when interpreting the results. Also, the results of a ground-based simulation can be greatly affected by the scenario and method used to conduct the experiments.

Item d is probably due to a difference in the perceived risk of performance errors as well as possible deficiencies in motion and visual cues in the ground-based simulator. Differences in cockpit instrumentation and control system characteristics could also contribute differences in combined pilot-vehicle error performance by means of variability in pilot behavioral properties such as gain, remnant, and thresholds of indifference to errors in performance.

Item e implies that the validity of extrapolating the results of a ground-based simulator to represent in-flight results can be affected by the type of disturbance. In this case the results of flying in calm air or turbulence were more accurately duplicated in the GBS than were the results of flying in wind shear.

C. COMPARISON OF FLIGHT-RECORDED AND COMPUTER-GENERATED TURBULENCE RESULTS

The Cooper-Harper handling quality ratings and selected measures of pilot-vehicle performance obtained with the flight-recorded wind profiles were compared to the analogous data obtained with the Dryden model of computer-generated turbulence. The comparison was made by computing linear regressions and correlation coefficients for the Cooper-Harper ratings and pilot-vehicle performance parameters using the rms level of the turbulence encountered on the approach flight path as the independent variable. The correlation coefficient is a measure of the goodness of the fit achieved by the linear regression and thus indicates the amount of variability in the data.

1. Cooper-Harper Ratings

Poor correlations between the Cooper-Harper ratings and the along-track rms turbulence level of the flight-recorded wind profiles (Task I) were obtained for all pilots. The correlation coefficients generally improved when data from runs with significant wind shears were deleted, although the regression lines did not change dramatically. Thus the wind shears were probably responsible for some of the variability in the data. Other possible sources of variability in the data will be discussed shortly.

Two striking dissimilarities were apparent when the Task I results were compared to the Cooper-Harper ratings obtained using the Dryden model of computer-generated turbulence (Task II). First, the correlation coefficients in the Task I data were much lower than in the Task II data and, second, the handling quality ratings in the Task I data were inferior to those from the Task II data.

There were some interesting similarities in the data obtained from all four pilots. For example, the ordinate intercepts of the regression lines were in good agreement, being at a Cooper-Harper rating of between 3 and 4 for all pilots. The handling qualities of the aircraft would therefore have either "Some mildly unpleasant deficiencies" or "Minor but annoying deficiencies," even in the absence of atmospheric disturbances. Also,

the slopes of the linear regression lines were quite similar, which indicates that the gradient of handling quality degradation due to atmospheric disturbances was about the same for all pilots.

Two conclusions can be made based upon the Cooper-Harper rating data. The first is to affirm that Cooper-Harper ratings do indeed degrade with each 2 or 3 ft/sec increase in the rms turbulence intensity. The second conclusion to be made is that the complex characteristics of the naturally-occurring turbulence used in this investigation (and which affect pilot ratings) were not adequately represented by the Dryden model of computer-generated turbulence.

2. Pilot-Vehicle Performance

The extreme deviations, mean and standard deviation of aircraft position, velocity, orientation, and control displacements were examined for correlation with measures of atmospheric disturbances. The best correlations, as reflected by the correlation coefficients resulting from linear regressions, were found between the extreme deviations and the rms along-track turbulence velocity.

In many instances the correlation coefficients improved after runs that contained significant wind shears were removed from the data. This indicated that some of the variability in the data was due to the wind shears. However, there were many other instances where the correlation coefficients were either unchanged or actually reduced after the significant wind shear cases were removed. This indicates that there are other properties of the flight-recorded wind profiles responsible for the variability in the data. The most likely property responsible for the variability is the so-called "patchy" characteristic of the turbulence, which creates an element of surprise in the pilot's disturbance regulation task and compounds the tracking error variance over the short-time durations characteristic of the patchy turbulence.

The same performance parameters examined for correlation with the rms along-track turbulence level from the flight-recorded turbulence (Task I) data were also examined using the computer-generated turbulence (Task II) data. Pilot-vehicle performance was linearly degraded with high correlation

as the rms level of the turbulence was increased. The relatively high correlation coefficients indicated low variability in the data. The trends in the Task II data were, therefore, quite different from the results obtained in Task I, which reflected low correlation coefficients among all the evaluation pilots. This result reaffirms our previous conclusion that the complex characteristics of the flight-recorded turbulence used in this investigation were not adequately represented by the relatively simple Dryden model of computer-generated turbulence.

3. Turbulence Realism and Patchiness Ratings

The pilots were required to rate the realism and patchy characteristic of the turbulence after each Task II evaluation flight. The results indicated that virtually all runs in which the turbulence realism was considered "Good" or "Very Good" were runs in which the patchiness of the turbulence was judged "About Right," that is, not "Too Continuous" or not "Too Patchy." Runs in which the turbulence realism was considered "Fair" or "Poor" were almost always runs in which the continuity of the turbulence was thought to be unrealistic. The conclusion to be made is that proper variation in the turbulence intensity is very important with respect to the pilots' perception of realism of the turbulence.

4. Summary of Findings

The following items summarize the findings discussed above and in Section IV.

a. The Dryden model of computer-generated turbulence did not adequately represent the naturally-occurring turbulence.

b. Variability in the handling quality ratings and pilot-vehicle performance measures was much higher for the naturally-occurring turbulence, even when the effects of wind shears were accounted for in the comparison with Dryden model turbulence.

c. The patchy characteristic of the naturally-occurring turbulence is believed to be at least partially responsible for findings a and b.

d. Patchiness is important with respect to the pilot's perception of the realism of the turbulence.

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APPENDIX

A SIMPLE MODEL OF FRONTAL SURFACE WIND SHEAR

Measured wind and temperature profiles for three of the flight-recorded wind profiles are shown in Fig. A-1. The profiles demonstrate shear layers associated with frontal surfaces that were encountered along the approach path. In each case the shear layer is characterized by an imbedded temperature inversion between two stable air masses, by a rapid decrease in the wind direction in the lower levels of the shear layer and a wind speed shear reducing the wind speed with reducing altitude through the front. The wind speed profiles often have a local minimum within the shear layer near its lower extremity.

When these wind profiles are replotted in terms of orthogonal earth-axis components, the individual components exhibit a simple linear shear through the frontal surface layer (Fig. A-2). This is consistent with a particular steady-state solution of the Navier-Stokes equations for a planar flow in a narrow layer with velocity boundary conditions at the upper and lower surfaces. A graphical description of the frontal shear layer and the boundary conditions are shown in Fig. A-3. If viscous forces dominate over local pressure gradients and the Coriolis acceleration, and if the eddy viscosity is assumed to be constant through the shear layer, then linear variations of each orthogonal component as a function of altitude satisfy the boundary-value problem defined in Fig. A-3. These conditions can be reasonably expected to prevail in a narrow (in macrometeorological terms) frontal shear layer.

The experimental data suggest a very simple wind model which can be used to provide realistic wind shears for ground-based simulator experiments. Designating the altitude of the lower extremity of the shear layer and its thickness respectively by h_o and H, and the wind speed and direction in the lower and upper air masses adjacent to the layer, (V_o, ψ_o) and (V_H, ψ_H),

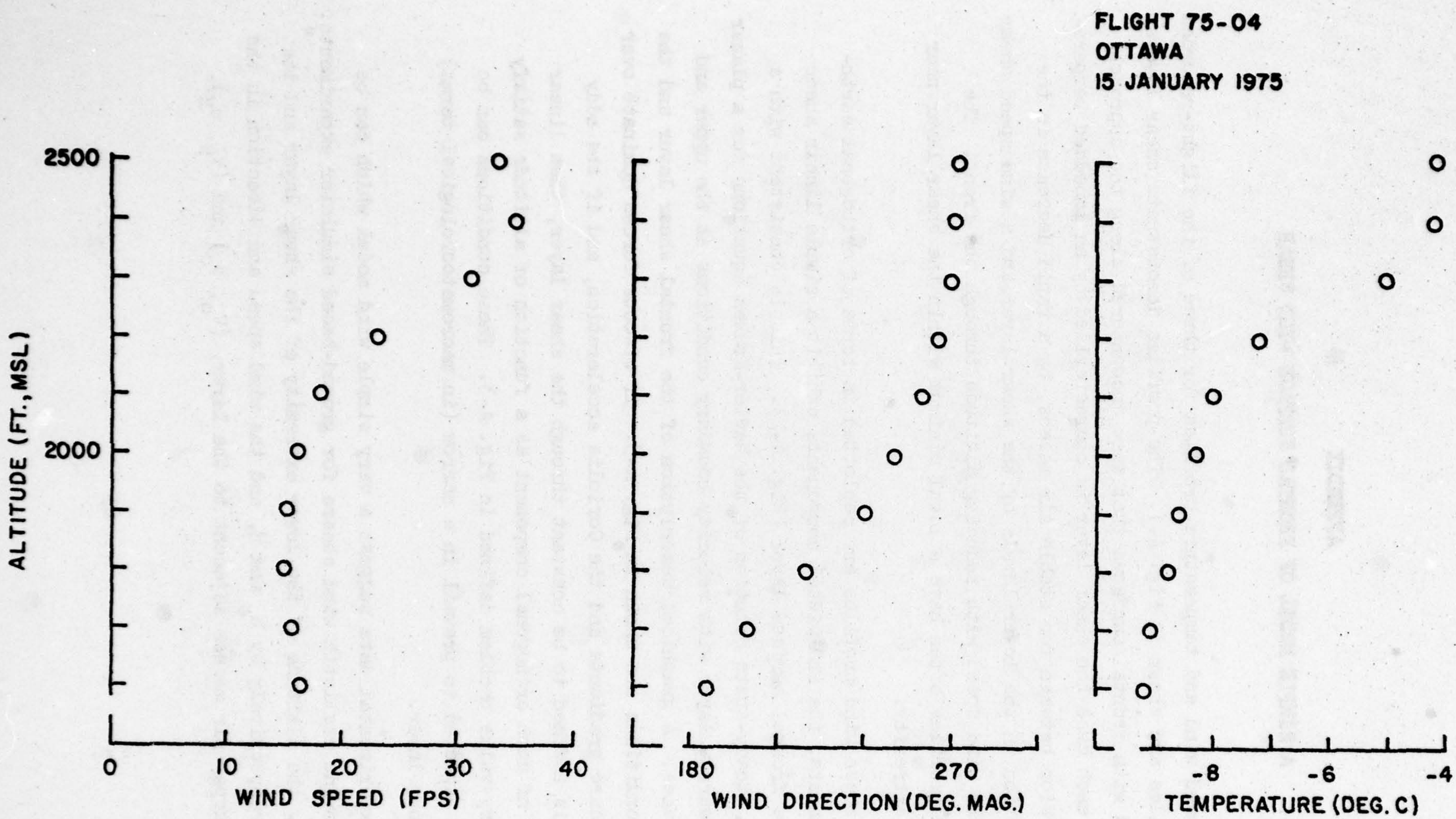


Figure A-1(a): Wind and Temperature Profiles

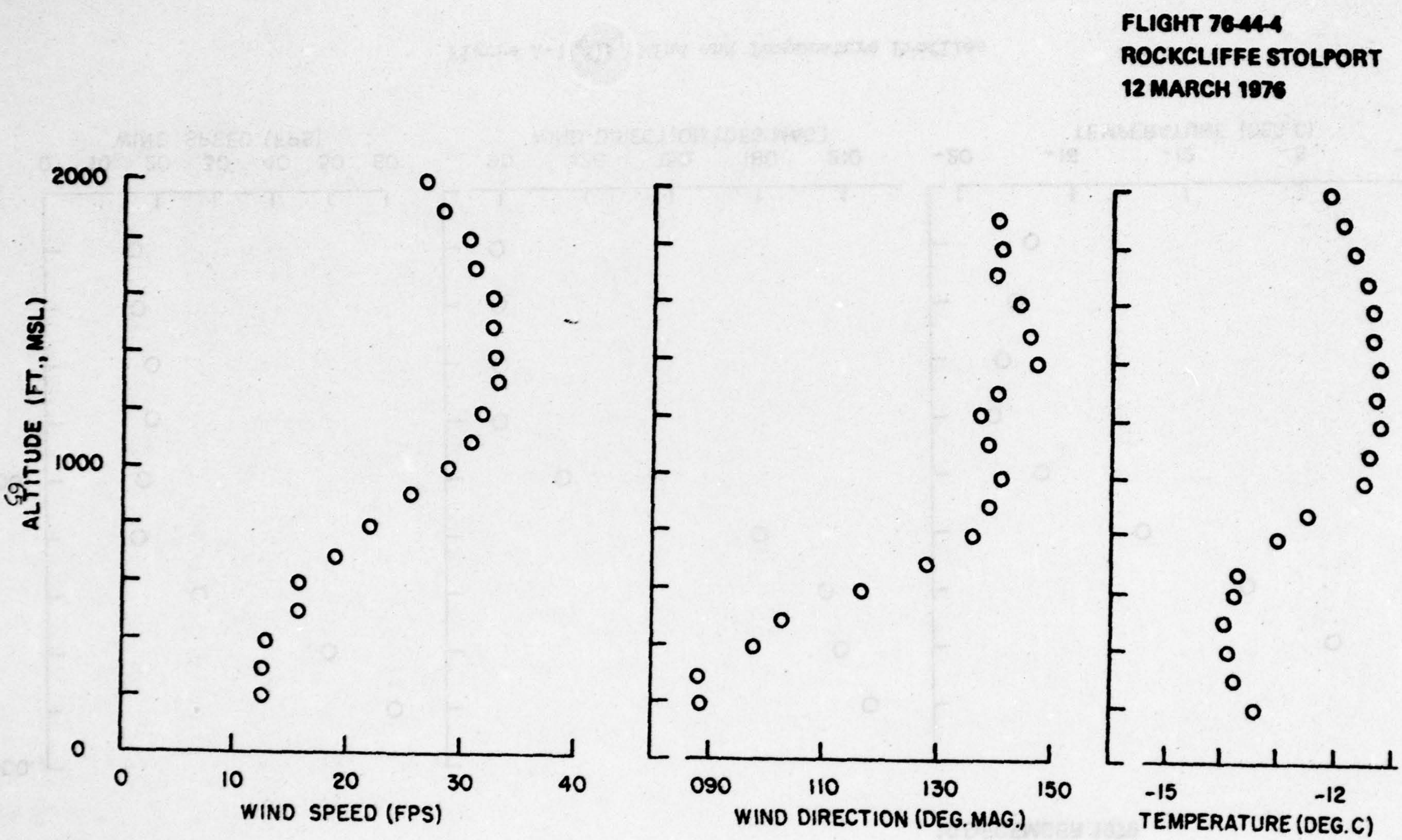


Figure A-1(b): Wind and Temperature Profiles

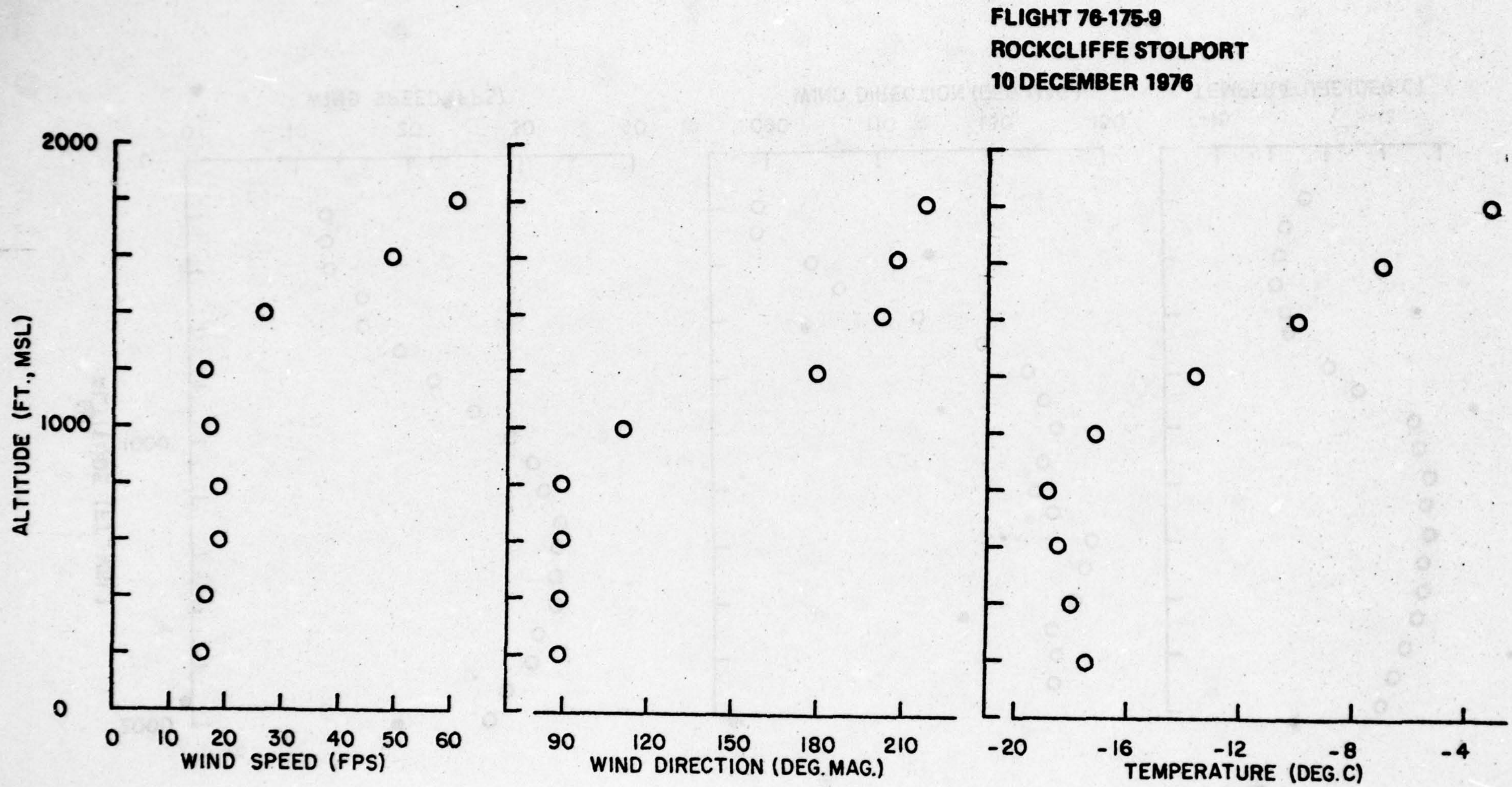


Figure A-1(c): Wind and Temperature Profiles

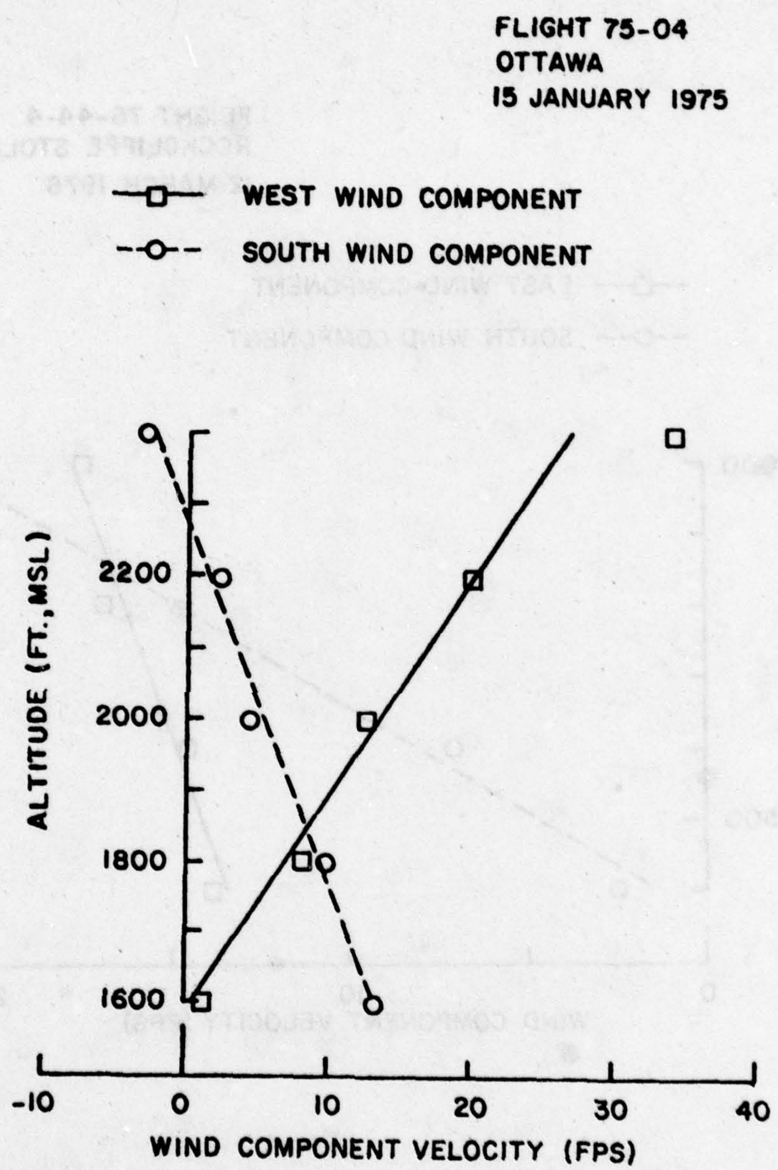


Figure A-2(a): Wind Velocity Components Through Shear Frontal Surface

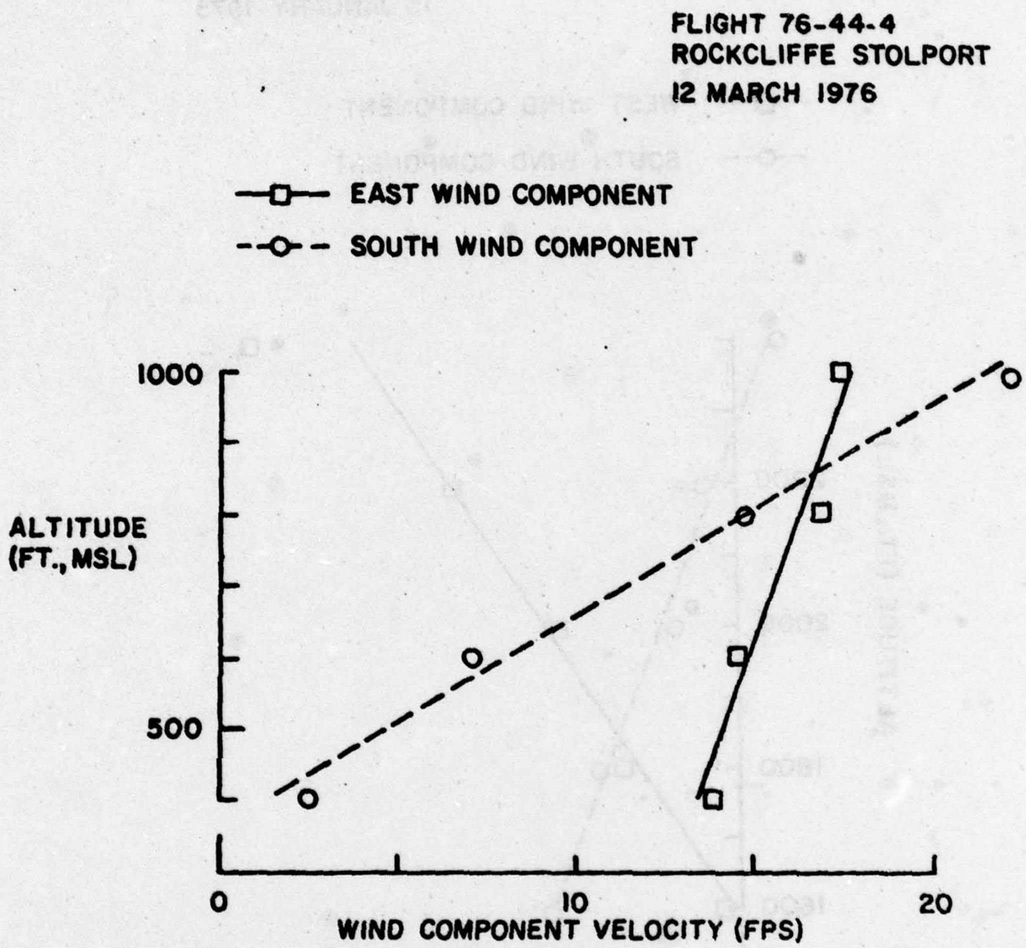


Figure A-2(b): Wind Velocity Components Through Shear Frontal Surface

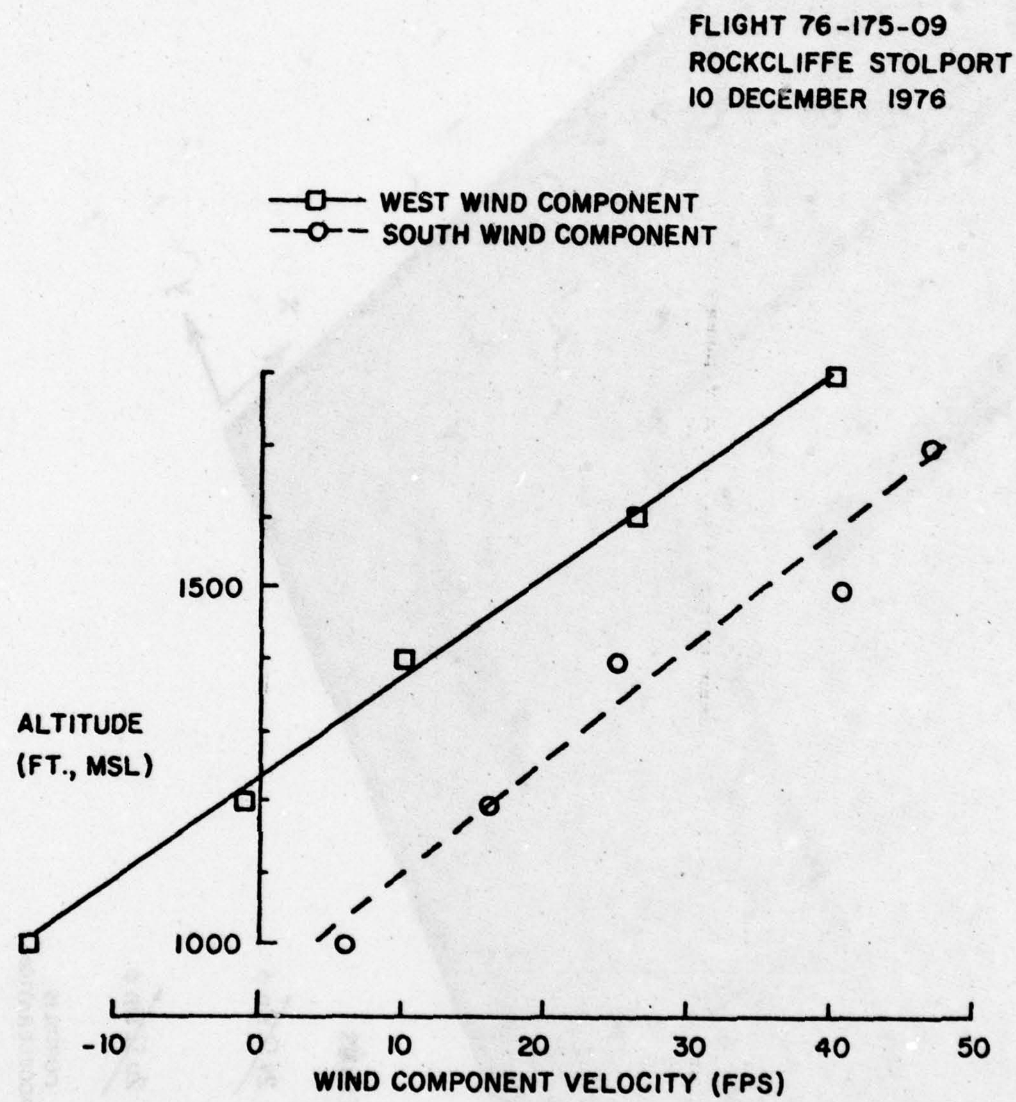
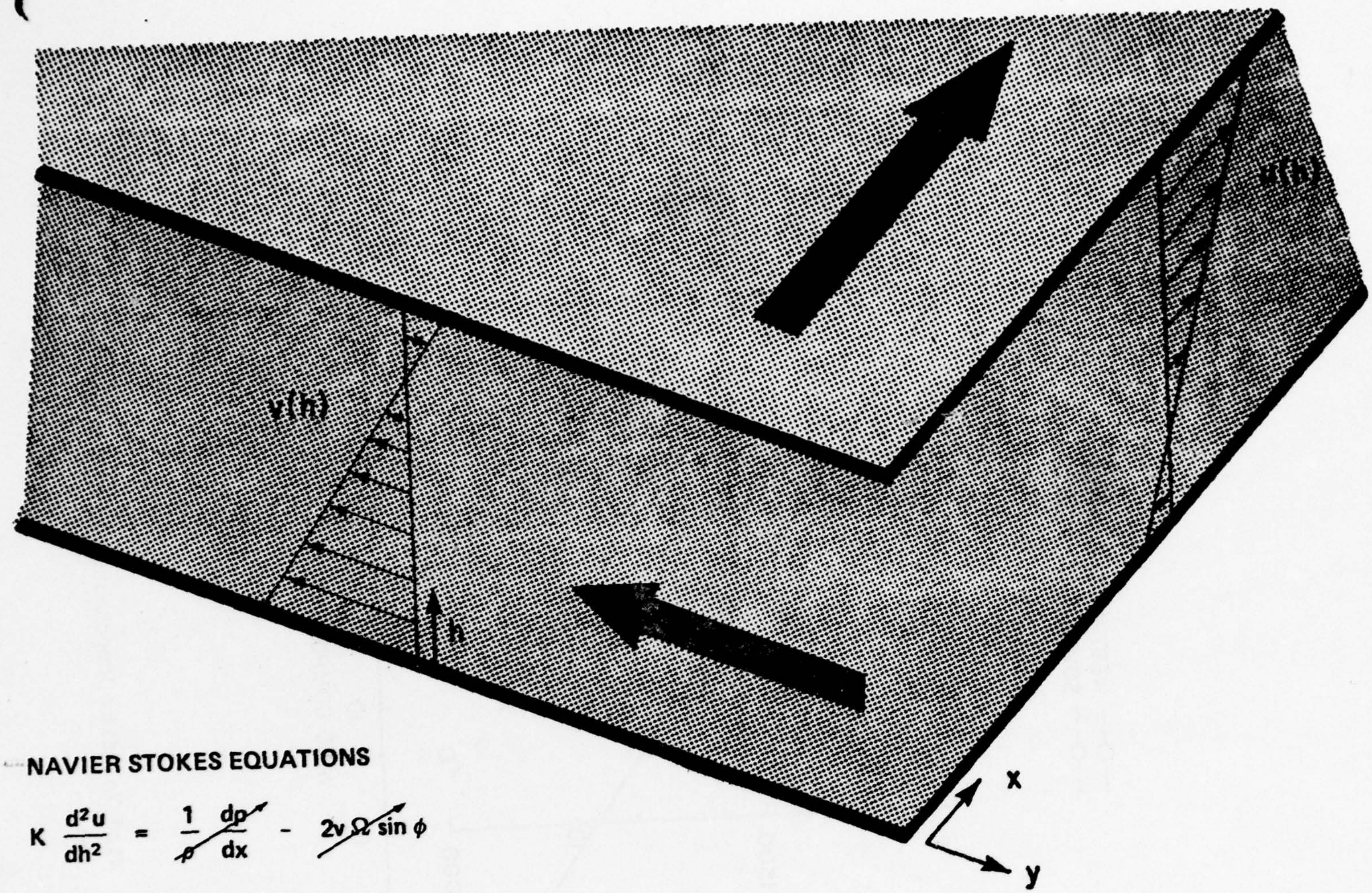


Figure A-2(c): Wind Velocity Components Through Shear Frontal Surface



NAVIER STOKES EQUATIONS

$$K \frac{d^2u}{dh^2} = \cancel{\frac{1}{\rho}\frac{dp}{dx}} - \cancel{2v\,\Omega \sin\phi}$$

$$K \frac{d^2v}{dh^2} = \cancel{\frac{1}{\rho}\frac{dp}{dy}} + \cancel{2u\,\Omega \sin\phi}$$

VISCOUS SHEAR	PRESSURE GRADIENT	CORIOLIS ACCELERATION

Figure A-3: Frontal Surface Shear Layer

respectively, the North and East wind components as a function of altitude, h, are given in the following equations:

For $h > h_o + H$ (i.e., above the shear layer):

$$u(h) = V_H \cos \psi_H$$
$$v(h) = V_H \sin \psi_H \tag{A-1}$$

For $h_o \leq h \leq h_o + H$ (i.e., within the shear layer):

$$u(h) = V_o \cos \psi_o + \left(\frac{h-h_o}{H}\right)(V_H \cos \psi_H - V_o \cos \psi_o)$$
$$v(h) = V_o \sin \psi_o + \left(\frac{h-h_o}{H}\right)(V_H \sin \psi_H - V_o \sin \psi_o) \tag{A-2}$$

For $h < h_o$ (i.e., below the shear layer):

$$u(h) = V_o \cos \psi_o$$
$$v(h) = V_o \sin \psi_o \tag{A-3}$$

The wind speed and direction are simply

$$V_w(h) = \sqrt{u(h)^2 + v(h)^2} \tag{A-4}$$

$$\psi_w(h) = \tan^{-1}[v(h)/u(h)] \tag{A-5}$$

Although the model is simple to the point of being mathematically trivial, it produces wind speed and directional shear profiles which have the essential characteristics of the measured profiles. Also, if the boundary conditions are properly selected, the wind speed shear will contain a local minimum within the shear layer. It can be shown that the necessary condition for this local minimum to exist is:

$$\cos \Delta\psi_w < V_o/V_H \tag{A-6}$$

where $\Delta\psi_w = \psi_H - \psi_o$

The three sample wind shear profiles shown in Fig. A-4 demonstrate that the wind shear model described above reproduces the overall characteristics of wind profiles measured during traverses of frontal shear layers on final approach. Although this is only one of many atmospheric phenomena which can produce large wind speed and wind direction gradients, it is a commonly occurring one and one which can be hazardous for aircraft with very low approach speeds.

It is believed that viable models of wind shears for other types of weather systems (e.g., thunderstorms) could also be developed. The models described in Ref. A-1 partially fulfill this need; however, it appears that they are overly complex and not well suited for realtime piloted aircraft simulations. Based on our experience with realtime piloted simulations, it is preferable to use simpler models of wind shears (e.g., Refs. A-2 and A-3). The model of Ref. A-1 uses three-dimensional table look-up routines to construct the wind profiles as a function of aircraft position. Perhaps the salient features of the various weather systems described in Ref. A-1 could be modeled in a manner similar to that described herein.

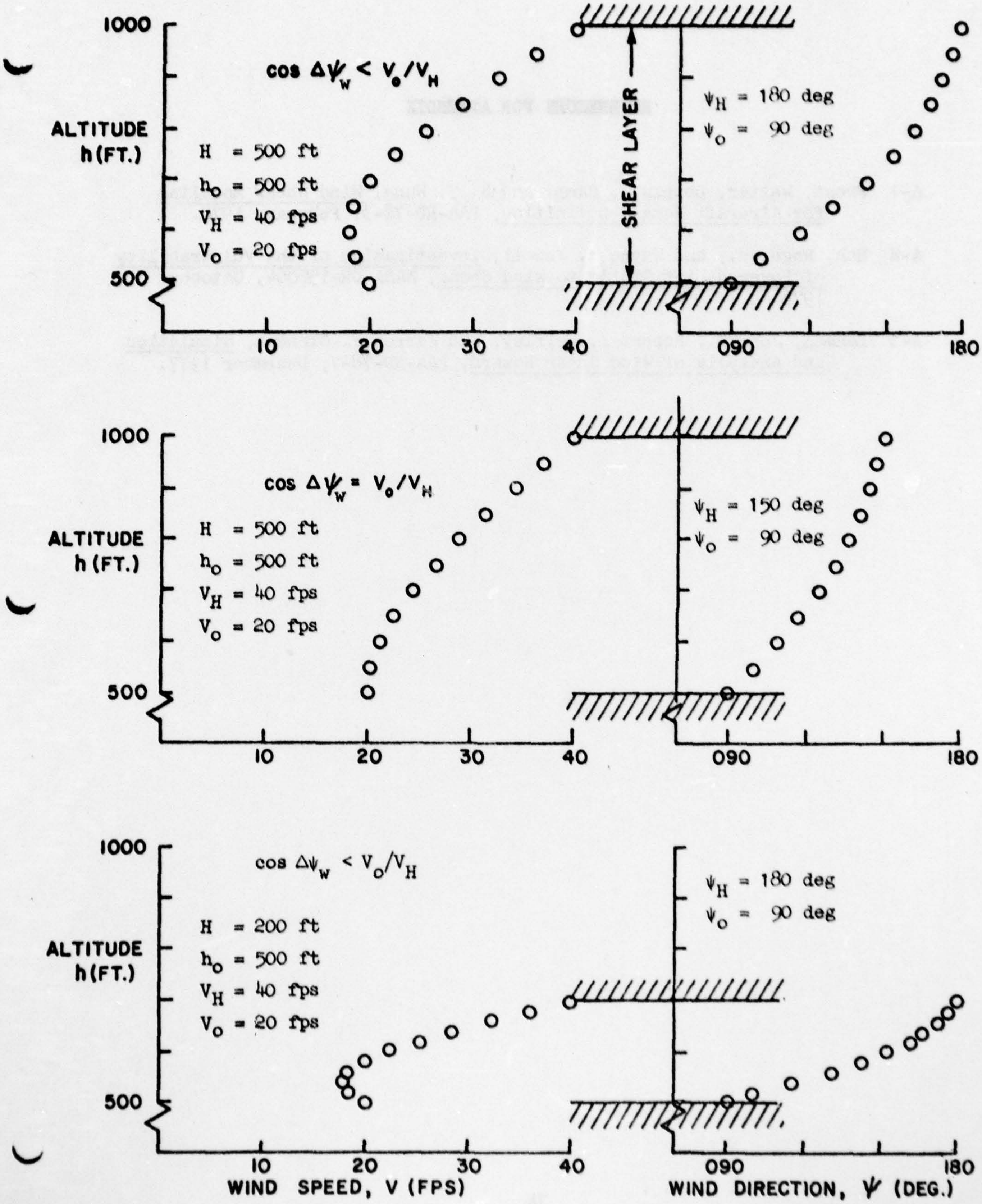


Figure A-4: Computed Wind Profiles

REFERENCES FOR APPENDIX

A-1 Frost, Walter, Dennis W. Camp, and S. T. Wang, Wind Shear Modeling for Aircraft Hazard Definition, FAA-RD-78-3, February 1978.

A-2 Hoh, Roger H., and Wayne F. Jewell, Investigation of the Vulnerability of Powered-Lift STOL's to Wind Shear, NASA CR-152064, October 1976.

A-3 Lehman, John M., Robert K. Heffley, and Warren F. Clement, Simulation and Analysis of Wind Shear Hazard, FAA-RD-78-7, December 1977.